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INVESTIGATION OF EXPLOSION GENERATED SV Lg WAVES IN 2-D HETEROGENEOUS CRUSTAL MODELS BY FINITE-DIFFERENCE METHOD

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A linear finite-difference (FD) method was used to compare the excitation of far-field P- and SV-waves generated by shallow dilatational sources in a suite of heterogeneous 2-D crustal models. The crustal models tested included simple layered structures, media with random velocity perturbations having Gaussian or self-similar autocorrelation functions, media with rough or gentle topography generated by Markov chains, and laminated media with sinusoidal folds. The numerical experiments were conducted by directing a broadband planar P- or SV-wave with appropriate incidence angle upon the testing models. The dilatational strain history at a shallow linear array of grid points was then recorded so that the far-field P- or SV(Lg)-waves from shallow dilatational sources could be inferred by use of the principle of reciprocity. The raw FD synthetics were deconvolved so as to represent the response due to explosion sources with a fixed yield. The mean peak amplitude of the synthetics for each model are compared to that for a reference model consisting of a simple layered medium. The average energy content in an appropriate signal window was measured as a complement to the amplitude meas-

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urement. Both approaches show essentially the same pattern of P/SV excitation, namely that models with topography consistently produce the strongest P-SV conversion among all types of crustal models. The introduction of interfaces (*e.g.*, dipping layers) alone does not by itself increase SV excitation with the required slowness range. Thus $m_b(P)$ - $m_b(Lg)$ appears to be smaller for models with topographic relief (*e.g.*, the Novaya Zemlya Island) than for models with dipping layers or folded sedimentary rocks (*e.g.*, Shagan River, eastern EKTS).

These synthetic results are consistent with observations for Novaya Zemlya (Nuttli, 1988) and Shagan River (Nuttli,1986), based on WWSSN film chip readings of Lg. The Novaya Zemlya, which has rough topography, has a higher Lg relative to P ($m_b(P) - m_b(Lg) = 0.04$) than does the somewhat flatter Shagan River test site ($m_b(P) - m_b(Lg) = 0.27$). However, Nuttli (1987) also obtained relatively low $m_b(Lg)$ for the Degelen Test Site, which is only 70 km away from Shagan River. If this Degelen-Shagan River bias is real, it is not explained by the FD results obtained to date. However, some recently archived high-quality digital seismograms recorded at the Chinese Digital Seismic Network indicate more Lg excitation (with respect to P) at Degelen than at Shagan River, which is consistent with our numerical results.

INVESTIGATION OF EXPLOSION GENERATED SV Lg WAVES IN 2-D HETEROGENEOUS CRUSTAL MODELS BY FINITE-DIFFERENCE METHOD

SUMMARY

A linear finite-difference (FD) method was used to compare the excitation of far-field P- and SV-waves generated by shallow dilatational sources in a suite of heterogeneous 2-D crustal models. The crustal models tested included simple layered structures, media with random velocity perturbations having Gaussian or self-similar autocorrelation functions, media with rough or gentle topography generated by Markov chains, and laminated media with sinusoidal folds. The numerical experiments were conducted by directing a broadband planar P- or SV-wave with appropriate incidence angle upon the testing models. The dilatational strain history at a shallow linear array of grid points was then recorded so that the far-field P- or SV(Lg)-waves from shallow dilatational sources could be inferred by use of the principle of reciprocity. The raw FD synthetics were deconvolved so as to represent the response due to explosion sources with a fixed yield. The mean peak amplitude of the synthetics for each model are compared to that for a reference model consisting of a simple layered medium. The average energy content in an appropriate signal window was measured as a complement to the amplitude measurement. Both approaches show essentially the same pattern of P/SV excitation, namely that models with topography consistently produce the strongest P-SV conversion among all types of crustal models. The introduction of interfaces (*e.g.*, dipping layers) alone does not by itself increase SV excitation with the required slowness range. Thus $m_b(P)$ - $m_b(Lg)$ appears to be smaller for models with topographic relief (*e.g.*, the Novaya Zemlya Island) than for models with dipping layers or folded sedimentary rocks (*e.g.*, Shagan River, eastern EKTS).

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INTRODUCTION

The seismic Lg wave is one of a number of regional phases that propagate in the continental lithosphere. Because the anelastic attenuation of 1-s period Lg wave is small in shield and geologically old stable regions, Lg wave amplitudes provide a useful tool for estimating 1-s period magnitude, such as m_b for small earthquakes and explosions (Nuttli, 1973). Furthermore, the radiation of Lg is more isotropic than that of P and S waves, which adds to its usefulness as a magnitude estimator for small events, because full azimuthal coverage is not essential and thus reliable magnitude determinations can be made from the data of only a few stations (Nuttli, 1986a). Following this line, Nuttli (1986a,b, 1987, and 1988) compared $m_b(P)$ - $m_b(Lg)$ at the Novaya Zemlya, Nevada Test Site, the Shagan River (eastern portion of East Kazakhstan Test Site) as well as the Degelen region (central portion of East Kazakhstan Test Site) as follows:

TABLE 1. $m_b(P)$ - $m_b(Lg)$ AT VARIOUS SITES

Site	$m_b(P)$ - $m_b(Lg)$	Reference
Novaya Zemlya	-0.11±0.02	Nuttli (1988)
Shagan River EEKTS	+0.04±0.12	Nuttli (1986b)
Degelen CEKTS	0.27±0.03	Nuttli (1987)
Nevada Test Site	-0.31±0.02	Nuttli (1986a)

The large difference between $m_b(P)$ - $m_b(Lg)$ values at Shagan River and Degelen, 0.23 magnitude unit, is quite surprising inasmuch as the two test sites are less than 70 km apart. Without knowing the actual values of the explosion yields at the Eastern Kazakhstan sites, it is not obvious at all to decide whether the $m_b(P)$ or the $m_b(Lg)$ values at Degelen are anomalous. The difference of 0.23 magnitude unit implies that, for an explosion of given yield, either the P-wave amplitudes at Degelen are 1.9 times larger than at Shagan or that the Lg-wave amplitudes are 1.9 times smaller at Degelen. Of course, both the P and Lg might be different between Degelen and Shagan for a given yield.

A number of possible explanations of the differences between m_b(P) - m_b(Lg) values at Shagan River and Degelen have been discussed (Nuttli, personal communication). The first is a difference in coupling of P and Lg waves at the two sites. Either the P-wave coupling is significantly more efficient at Degelen than at Snagan, or the Lg-wave coupling at Degelen is less than at Shagan. A second possible explanation, somewhat related to the first, is that m_b(P) is larger at Degelen because of testing practices. Station sampling bias might be considered as the third explanation, but the data Nuttli used indicate that there is little such bias, if any. A fourth explanation is related to the fact that most of the Degelen explosions are smaller than those at Shagan, and thus the reported m_b(P) values for the Degelen events might be overestimated because only stations recording large amplitude P waves were used to obtain the International Seismological Center m_b(P) values. However, Nuttli (1987) reported that the largest Degelen events of 20 February 1975, 26 March 1978, 28 July 1978, and 29 November 1978 have an average m_b(P) - m_b(Lg) value of 0.27, the same value as for the entire set of Degelen explosions. The fifth possible explanation is that the slope of m_b(Lg) versus m_b(P) is less than unity because of differences in corner frequencies in spectra.

It is the purpose of this report to check the first hypothesis. CEKTS has considerable topographic relief (Rodean, 1979) whereas EEKTS consists of folded sedimentary rocks (Nordyke, 1973). We therefore investigated several 2-D models for the excitation of SV Lg as well as P waves using linear elastic finite-difference calculations. These simplistic models simulate the excitation of far field SV and P waves from dilatational line sources embedded in 2-D heterogeneous models with and without free surface topography.

Strictly speaking, no adequate analytical theory is available to model the near-source crustal effect of the type investigated here. Lg is thought to be superpositions of higher Rayleigh and Love modes. In terms of higher modes, the complexities of mode conversions and scatter-

ing at lateral inhomogeneities are prohibitive for analytical treatment. In addition, it is not possible to tell how much energy is present in the various structures if the concept of modes has any meaning at the wavelengths involved. The problem becomes more tractable if one regards Lg as SH or SV waves trapped in the crust and having turning points above the Moho. As a crude approximation [illegible] Lg [illegible] modeled [illegible] as SH or SV waves incident on the structure to be tested at an angle such that the phase velocity is in the observed 4.2 to 4.5 km/sec range (Barker [illegible] [illegible] et al., 1984).

FINITE DIFFERENCE CALCULATIONS

The 2-D [illegible] popularized by Kelly *et al.* (1976) is used with the absorbing boundary conditions [illegible] and Engquist, 1977; Emerman and Stephen, 1983) on both the sides and the bottom of the grid. Free surface boundary conditions are the default on the top of the grid, since these are suitable for use in models with flat or arbitrary polygonal topography [illegible] difference code has been utilized in the modeling of effects [illegible] due to the geological structure of Yucca Valley, NTS (McLaughlin *et al.*, [illegible]), the topography at Ahaggar Plateau (McLaughlin and Jih, 1986a), as well as the [illegible] Rayleigh waves by rough topography (McLaughlin and Jih, [illegible]) and [illegible] heterogeneity (McLaughlin and Jih, 1987).

The [illegible] used in these experiments consist of the following five types:

1. Gaussian [illegible] a 2-D white velocity field with 2-D Gaussian spatial [illegible] scatterers (*i.e.*, mean grain size, *a*), which turns out to [illegible] correlation distance.

2. self-similar media generated by modulating the wavenumber-wavenumber spectra of a white velocity field with the 2-D Fourier transform, $\frac{a^2}{1+k^2a^2}$, of a special Von Karmon correlation function.

3. folded layers of sinusoidal shape with specified wavelength, amplitude and velocity profile

4. dipping sedimentary layers with specified velocity profile.

5. simple layered models.

On some of the models there was superimposed fairly rough topography generated by a Markov chain. Fourteen 2-D geologic structures were used to calculate the excitation of far-field SV and P waves from dilational line sources. Some typical simplistic models are shown in Figures 1 and 2. Similar random media have been used widely in modeling the scattering or propagation of either acoustic or elastic waves by the finite-difference method (Frankel and Clayton, 1984, 1986; Levander and Hill, 1985; Levander, 1985; Frankel and Wennerberg, 1987; McLaughlin and Jih, 1987). In the heterogeneous portion of the grid, the S-wave velocity (β) was assumed to be directly related to the P-wave velocity (α) by the following linear relationship: for $\alpha < 2.8$, $\beta = 0.45\ \alpha$; for $3.2 < \alpha < 4.8$, $\beta = 0.50\ \alpha$; for $\alpha > 5.2$, $\beta = 0.59\ \alpha$; and linear interpolation was used for the transition intervals. These heterogeneous media are then embedded into a homogeneous half space with P- and S-wave velocities of 6 and 3.55 km/sec respectively.

The incident wave is a broadband Ohnaka planar SV wave with apparent velocities of 4.5 km/sec incident upon these models. The dilational strain was recorded at an array of locations with an average depth of 0.5 km in the grid. By use of the reciprocity principle, the displacement response at far distance (teleseismic) was determined for a dilational line source with a

von Seggern and Blandford (1972) reduced displacement potential for 50KT in hard rock. The same technique has been utilized previously in modeling the effects of the geologic structure of Yucca Valley (McLaughlin *et al.*, 1987) as well as that of the topographic configuration of Ahaggar mountain on teleseismic $m_b(P)$ (McLaughlin and Jih, 1986). One minor difference is that here the incidence angles of the incoming SV- and P wave were 52^o and 20^o respectively, corresponding to the appropriate apparent velocity range. To assure that the initial incoming wave lies completely in the homogeneous half space, we have selected grid dimensions of 250 by 430 and 250 by 250 for SV- and P-wave simulations, respectively. The mesh spacings were $\Delta x = \Delta z = 0.050$km. Thus the two grids are of the same width 12.5km and two different depths: 21.5km and 12.5km. Due to the limitation of the grid size, the heterogeneous crustal layers were set to 2 or 3 km. This distinction with the realistic crustal depth should be kept in mind when interpreting the results. Although the temporal spacing was 0.005 sec, the band beyond 5 Hz is less reliable due to the inevitable grid dispersion of finite-difference simulation.

The FD synthetics were deconvolved/convolved so as to represent the outgoing waves due to the same explosion line source in each model. The results from these simulations are presented in Table 2. The excitation of P and SV waves for each model are referenced to the excitation for a uniform 2 km layer ($\alpha = 5.0$km/s, $\beta = 2.74$km/s) over a uniform half space ($\alpha = 6.0$km/s, $\beta = 3.55$km/s). The models are arranged in order of decreasing SV Lg excitation relative to the reference model (j=0). Data shown under columns P and Lg are $\log(P_j/P_0)$ and $\log(Lg_j/Lg_0)$ respectively, where both P and Lg are the averaged peak amplitude measurement of the synthetics derived from deconvolution, low pass filtering etc.

TABLE 2. COMPARISON OF EXPLOSION P AND SV Lg EXCITATION

model	P	Lg	P-Lg	Description of the model
0	0.000	0.000	0.000	1-uniform layer (5+0%, 2km thick)
1	-0.207	0.202	-0.409	rough TOPO + 1 uniform layer (5+0%, 2km thick)
2	-0.006	0.132	-0.139	gentle TOPO + self-similar layer (5+10%, 2km)
3	-0.196	0.110	-0.305	rough TOPO + Gaussian layer (5+10%, 2km)
4	-0.023	0.073	-0.096	gentle TOPO + 1 uniform layer (5+0%, 2km)
5	-0.034	0.044	-0.078	self-similar layer (5+10%, 2km thick)
6	-0.162	0.019	-0.181	folded sinusoidal layers(L=2,H=2.5,5+20%)
7	-0.031	0.014	-0.045	folded sinusoidal layers(L=2,H=2.5,5+10%)
8	-0.134	-0.037	-0.098	self-similar layer (5+20%, 2km thick)
9	-0.029	-0.037	0.008	folded sinusoidal layers(L=5,H=2.5,5+10%)
10	0.003	-0.058	0.061	2-Gaussian layer (4.5+10%/5+10%, total 2km)
11	0.019	-0.091	0.110	steeply dipping layers (52^o)
12	0.011	-0.093	0.104	gently dipping layers (26^o)
13	0.018	-0.137	0.155	steeply dipping layers (-52^o)
14	0.009	-0.143	0.152	gently dipping layers (-26^o)

Some observations are immediate:

1. For self-similar models, weak variation in the medium velocities causes more Lg generation.

2. Dipping layers (models 11 through 14) generate smaller Lg than the normalizing model.

3. Media with topography (e.g. models 1 through 4) which represent CEKTS all generate more Lg than the normalizing model.

4. Dipping layers (models 11 through 14) are more efficient than all other models for P excitation.

5. m_b(P) - m_b(Lg) at EEKTS (e.g. models 11 through 14) are larger than for any other model.

We have noticed that the smoothing of the interface between the sediment layer and the half space would not significantly affect the result.

Observations 2,3,4 and 5 can be explained easily as that topography creates more apparent explosion P-SV(Lg) coupling. The introduction of interfaces alone does not of itself increase SV excitation with the required slowness range. Although this result is in seeming contradiction to Nuttli's (1987) CEKTS-EEKTS observation, our previous numerical experiments tend to support this explanation.

As a comparison, the results corresponding to frequency-domain measurements are also presented for the 0.5-1.0 Hz bandwidth in Table 3. Again, the average spectral level of the dilatational strain history in the 0.5-1.0 Hz bandwidth from the array of locations is determined relative to a reference model. Note that the results under the Lg and P-Lg columns in Table 3 follow the same pattern as the time-domain approach with the exception of the folded models and the 20% self-similar model.

TABLE 3. EXPLOSION EXCITED P AND SV Lg ON 0.5-1.0 Hz

model	P	Lg	P-Lg	Description of the model
0	0.000	0.000	0.000	reference model
1	-0.400	0.083	-0.483	rough TOPO+uniform layer(5+0%,2km)
2	-0.049	0.057	-0.106	gentle TOPO+self-similar layer(5+10%,2km)
3	-0.363	0.063	-0.426	rough TOPO+Gaussian layer(5.0+10%,2km)
4	-0.180	0.019	-0.199	gentle TOPO+uniform layer(5+0%,2km)
5	0.016	0.009	0.007	self-similar layer(5+10%,2km)
6	0.099	-0.031	0.130	folded sinusoidal layers(5+20%,L=2,H=2.5)
7	0.058	-0.101	0.159	folded sinusoidal layers(5+10%,L=2,H=2.5)
8	-0.026	-0.049	0.023	self-similar layer(5+20%,2km)
9	0.015	-0.163	0.178	folded sinusoidal layers(5+10%,L=5,H=2.5)
10	0.083	-0.007	0.090	2-Gaussian layer(4.5+10%/5.0+10%,2km)
11	-0.008	-0.048	0.040	steeply dipping layers(52^o)
12	-0.024	-0.057	0.033	gently dipping layers(26^o)
13	0.015	-0.086	0.101	steeply dipping layers(-52^o)
14	-0.001	-0.103	0.102	gently dipping layers(-26^o)

DISCUSSIONS AND CONCLUSIONS

The method of finite-difference was used to simulate the excitation of explosion generated far-field P and SV Lg waves in various models of crustal heterogeneity. While we continue to experiment with various models, our preliminary results indicate that P to SV conversion is strongly enhanced by velocity variation in the vicinity of rough topography and the introduction of low velocity layers near the surface. The introduction of interfaces alone does not of itself increase SV excitation with the required slowness range.

These synthetic results are consistent with observations for Novaya Zemlya (Nuttli, 1988) and Shagan River (Nuttli,1986), based on WWSSN film chip readings of Lg. The Novaya Zemlya, which has rough topography, has a higher Lg relative to P ($m_b(P)$ - $m_b(Lg)$ = 0.04) than does the somewhat flatter Shagan River test site ($m_b(P)$ - $m_b(Lg)$ = 0.27). However, Nuttli (1987) also obtained relatively low $m_b(Lg)$ for the Degelen Test Site, which is only 70 km away from Shagan River. If this Degelen-Shagan River bias is real, it is not explained by the FD results obtained to date. However, some recently archived high-quality digital seismograms recorded at the Chinese Digital Seismic Network indicate more Lg excitation (with respect to P) at Degelen than at Shagan River, which is consistent with our numerical results (Figure 41).

Although we cannot presently explain Nuttli's (1987) Degelen results, we predict substantial variations in SV Lg excitation by explosions embedded in crustal heterogeneity. It seems that P-to-SV is not the only mechanism for explosion Lg excitation, so it is necessary to investigate the excitation of SH(Lg) as well.

A possibility is that Nuttli's m_b:Lg relationship might be related to Rayleigh-to-P conversion away from the immediate location of the source. Our numerical simulations treated only the P-S conversions that might occur within a few km of the source, and given some simple

models. If either the Rayleigh excitation or the Rayleigh scattering is different for CEKTS and EEKTS, then we could see the difference in Rayleigh to Lg. Since the two locations are only 70 km apart, the Rayleigh-to-Lg difference would presumably have to occur in the first 20-25 seconds. Thus it seems necessary to examine if the P-coda are different for Degelen and Shagan in the first 20-25 seconds. Similarly, P-SV conversion could be happening further away from the source than we are modeling. It is also possible that the non-linear source effects might produce larger SV at one site versus another. These hypothesis as well as the 3-dimensional effects were not addressed in our current experiments.

Baumgardt (personal communication, 1987) pointed out that the observations at NORSAR for Degelen and Shagan events (Ringdal, 1982) did not show the bias, and he proposed another explanation for Nuttli's observations as that Nuttli's Degelen observations were made almost entirely with stations to the south, whereas the Shagan data contain observations from the NW at Scandinavian stations. His station corrections for Q may therefore have been biased. Baumgardt (1985) proposed that Lg loses energy as it crosses the Urals on its way to the Scandinavian stations, and this loss may not be accounted for in Nuttli's Q. It is interesting to note that in Nuttli's (1986b) original paper on Shagan events, his revised Q_0 values are the same as or less than the original Q_0 values for all the Scandinavian stations. The reduced Q_0 values resulted because the Scandinavian m_b(Lg) values were less than average.

The finite-difference results in Figures 39 and 40 also show negatively correlated P and SV energy. This provides a preliminary explanation of the success of the unified yield estimator (U.S. Congress, Office of Technology Assessment, 1988). It seems that measuring all possible phases reduces the effects of uneven energy release on source size estimation. To understand this issue in a more quantitative manner, and to derive an optimal weighting scheme to combine all phases, theoretical studies with numerical simulations are necessary.

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McLaughlin, K. L. and R.-S. Jih (1986a), Scattering from near-source topography: teleseismic observations and numerical 2-D explosive line source simulations, Section III of *Report AFGL-TR-86-0159 (TGAL-86-03)* Teledyne Geotech, Alexandria, VA (ADA 183013).

McLaughlin, K. L. and R.-S. Jih (1986b), Finite-difference simulations of Rayleigh wave scattering by 2-D rough topography, *Report AFGL-TR-86-0269 (TGAL-86-09)*, Teledyne Geotech, Alexandria, VA (ADA 179190).

McLaughlin, K. L. and R.-S. Jih (1987), Finite-difference simulations of Rayleigh wave scattering by shallow heterogeneity, *Report AFGL-TR-87-0322 (TGAL-87-02)*, Teledyne Geotech, Alexandria, VA (available through NTIS).

Nordyke, M. D. (1973), A review of Soviet data on the peaceful uses of nuclear explosions, *Report UCRL-51414*, Lawrence Livermore Laboratory, University of California, CA (available through NTIS).

Nuttli, O. W. (1986a), Yield estimates of Nevada Test Site explosions obtained from seismic Lg waves, *J. Geophys. res.*, **91**, 2137-2151.

Nuttli, O. W. (1986b), Lg magnitudes of selected East Kazakhstan underground explosions, *Bull. Seism. Soc. Am.*, **76**, 1241-1251.

Nuttli, O. W. (1987), Lg magnitudes of Degelen, East Kazakhstan, underground explosions, *Bull. Seism. Soc. Am.*, **77**, 679-681.

Nuttli, O. W. (1988), Lg magnitudes and yield estimates for underground Novaya Zemlya nuclear explosions, *Bull. Seism. Soc. Am.*, **78**, 873-884.

Ringdal (1983), Magnitude from P coda and Lg using NORSAR data, in *Scientific Report No.2-82/83, NORSAR Semiannual Technical Summary, 1 Oct 82 - 31 Mar 83*, Linda B. Tronrud (ed.), 72-80 (available through NTIS).

Rodean, H. C. (1979), ISC events from 1964 to 1976 at and near the nuclear testing ground in eastern Kazakhstan, *Report UCRL-52856*, Lawrence Livermore Laboratory, University of California, CA (available through NTIS).

U.S. Congress, Office of Technology Assessment (1988), Seismic verification of nuclear testing treaties, *OTA-ISC-361*, U.S. Government Printing Office, Washington, DC.

GENERAL REFERENCES

Der, Z. A., M. E. Marshall, A. O'Donnell, T. W. McElfresh (1984), Spatial coherence structure and attenuation of the Lg phase, site effects, and the interpretation of the Lg coda, *Bull. Seism. Soc. Am.*, **74**, 1125-1147.

Der, Z. A., T. W. McElfresh, R. Wagner, and J. Burnetti (1985), Errata to "Spectral characteristics of P waves from nuclear explosions and yield estimation" *Bull. Seism. Soc. Am.*, **75**, 1222.

Der, Z. A., C. P. Mrazek, E. Smart, and B. W. Barker (1978), Some aspects of Lg and Pg propagation, *Report SDAC-TR-78-11*, Seismic Data Analysis Center, Teledyne Geotech, Alexandria, VA (available through NTIS).

Der, Z. A., A. O'Donnell, T. W. McElfresh, R. Jutila, J. A. Burnetti, M. Marshall, M. Silk and R. Gordon (1982), A study of seismic wave propagation at regional distances in five areas of the world, *Report VSC-TR-82-14*, Seismic Data Analysis Center, Teledyne Geotech, Alexandria, VA (available through NTIS).

Der, Z. A., A. O'Donnell, P. J. Klouda (1981), As investigation of attenuation, scattering and site effects on regional phases, *Report VSC-TR-81-11*, Seismic Data Analysis Center, Teledyne Geotech, Alexandria, VA (available through NTIS).

Herrmann, R. B. (1987), Lg wave excitation and propagation in the presence of one-, two-, and three-dimensional heterogeneities, *Report AFGL-TR-87-0229*, St. Louis Univ., St. Louis, MO (available through NTIS).

Teledyne Geotech (1980), Studies of seismic wave characteristics at regional distances, *Report AL-80-1*, Teledyne Geotech, Alexandria, VA (available through NTIS).

FIGURE CAPTIONS

Figure 1. Typical geological models used in the finite-difference simulations in this report, which included: (A) model 5: a 2 km thick self-similar layer of mean $\alpha = 5$ km/sec and 10% variation, superimposed on a homogeneous half space with $\alpha = 6$ km/sec. (B) A 2 km thick Gaussian layer of mean $\alpha = 5$ km/sec and 10% variation, mean grain size = 1 km. (C) model 7: a 3 km thick sedimentary rock of folded layers with sinusoidal shape. The folded layers have wavelength 2 km, peak-to-peak amplitude 2.5 km. Each layer is uniform in material property, and the profile of α is Gaussian distributed with mean 5 km/sec, $\nu = 10\%$. The interface between the half space and the folded layers is smoothed. (D) model 9: similar to (C) except that the folded layers have wavelength 5 km.

Figure 2. (E) model 3: a rough topography superimposed on a 2 km thick Gaussian layer. (F) Same as (E) except that the layer is uniform with $\alpha = 5$ km/sec. (G) model 2: similar to (E), except for self-similar velocity variation and different topography. (H) model 4: same as (G) except for uniform layer. The rough topography was generated by a Markov chain with larger transition probability, which yielded "more frequent" small-scale elevation changes.

Figure 3. Model 2. P wave in a half space ($\alpha = 6.0$ km/s, $\beta = 3.55$ km/s) incident upon a 2 km layer with average P-wave velocity of 5 km/s and a self-similar 10% rms velocity variation superimposed by a gentle topography (indicated in the 0 sec frame). The S-wave velocity is assumed to be proportional to the P-wave velocity. Darkness of the snapshots are proportional to the displacement amplitude. Snapshots of the displacement field are shown at 1 second intervals. The dilatational strain is recorded at 32 locations at a depth of 0.5 km in order to infer the excitation of far-field P waves from explosion sources. Although absorbing boundary conditions are used, care must be taken to avoid residual reflections from the sides of the grid.

Figure 4. Model 7. Same as Figure 3 except that a 3 km thick sedimentary rock of folded layers with sinusoidal shape. The folded layers have wavelength 2 km, peak-to-peak amplitude 2.5 km. Each layer is uniform in material property, and the profile of α is Gaussian distributed with mean 5 km/sec, $\nu = 10\%$. The interface between the half space and the folded layers is smoothed (see Figure 1 (C)).

Figure 5. Model 8. Same as Figure 3 except the layer has P-wave velocity of 5 km/s and a self-similar 20% rms velocity variation (indicated in the 0 sec frame).

Figure 6. Model 14. Same as Figure 5 except that the gently dipping layers totaling 3 km thick are superimposed on the half space. The sedimentary layers have Gaussian distributed profile with mean 5 km/sec, $\nu = 10\%$.

Figure 7. Model 2. S wave in a half space ($\alpha = 6.0$ km/s, $\beta = 3.55$ km/s) incident at 52^o upon a 2 km self-similar layer with average P-wave velocity of 5 km/s and 10% rms velocity variation superimposed by a gentle topography (indicated in the 0 sec frame). The dilatational strain is recorded at 32 locations at a depth of 0.5 km in order to infer the excitation of far-field S waves from explosion sources.

Figure 8. Model 5. Same as Figure 7 except that the self-similar layer is flat(indicated in the 0 sec frame).

Figure 9. Model 9. Same as Figure 7 except that the 3 km thick low velocity layer consists of lightly folded (5 km wavelength, 2.5 km amplitude) 0.5 km thick layers with 10% rms velocity variation with respect to an average velocity of 5 km/s.

Figure 10 Model 14. Same as Figure 7 except that the half space is superimposed by gently dipping layers totaling 3 km thick. The sedimentary layers have Gaussian distributed profile with mean 5 km/sec, v = 10%.

Figure 11. Model 1. Synthetic far-field P- (top) and SV-wave (bottom) inferred by the principle of reciprocity. The original dilatational strain history (5 Hz low-pass) responding to incident broadband P or SV plane wave recorded at 32 locations at 0.5 km depth in the reference model. Shown here are the deconvolved synthetics corresponding to VSB 50 KT in hard rock. The peak amplitude of these synthetics was measured and compared to the average peak amplitude of the reference model.

Figure 12. Same as Figure 11 except for model 2.

Figure 13. Same as Figure 11 except for model 3.

Figure 14. Same as Figure 11 except for model 4.

Figure 15. Same as Figure 11 except for model 5.

Figure 16. Same as Figure 11 except for model 6.

Figure 17. Same as Figure 11 except for model 7.

Figure 18. Same as Figure 11 except for model 8.

Figure 19. Same as Figure 11 except for model 9.

Figure 20. Same as Figure 11 except for model 10.

Figure 21. Same as Figure 11 except for model 11.

Figure 22. Same as Figure 11 except for model 12.

Figure 23. Same as Figure 11 except for model 13.

Figure 24. Same as Figure 11 except for model 14.

Figure 25. Average spectral ratio as a function of frequency, $Log(\frac{P_1}{P_0})$ (upper) and $Log(\frac{Lg_1}{Lg_0})$ (lower), of the Model 1 relative to the reference model. P wave response of model 1 in the 0.5 to 1.0 Hz range is deficient with respect to the reference model by 0.348 log units, while the S wave response is 0.063 log unit above the reference model. Vertical bars represent the standard error of a single observation.

Figure 26. Same as Figure 25 except for model 2.

Figure 27. Same as Figure 25 except for model 3.

Figure 28. Same as Figure 25 except for model 4.

Figure 29. Same as Figure 25 except for model 5.

Figure 30. Same as Figure 25 except for model 6.

Figure 31. Same as Figure 25 except for model 7.

Figure 32. Same as Figure 25 except for model 8.

Figure 33. Same as Figure 25 except for model 9.

Figure 34. Same as Figure 25 except for model 10.

Figure 35. Same as Figure 25 except for model 11.

Figure 36. Same as Figure 25 except for model 12.

Figure 37. Same as Figure 25 except for model 13.

Figure 38. Same as Figure 25 except for model 14.

Figure 39. Averaged P and SV(Lg) peak amplitudes of array of shallow explosions in fourteen crustal models sorted with the $\log_{10}(Lg/Lg_0)$ values. Several observations are obvious: (1) Dipping layers (models 11 through 14) generate smaller Lg than the normalizing model, while they all generate more P than the reference model. (2) Media with topography (e.g. models 1 through 4) which represent CEKTS all generate more Lg than the normalizing model, while they excite less P due to strong P to S conversion. (3) Dipping layers (models 11 through 14) are more efficient than all other models for P excitation. Thus $m_b(P)$ and $m_b(Lg)$ appear to be negatively correlated.

Figure 40. Same as Figure 39 except the P and SV(Lg) excitations are measured with the averaged spectral content in [0.5,1] Hz band. Crustal models with topography generate more Lg and less P than models with dipping layers, same as the result derived from peak amplitude measurement.

Figure 41. Short period seismograms of two Shagan events 87171 (78.74E, 49.91N, mb=6.1) and 87347 (78.85E, 49.96N, mb=6.1), and a Degelen event 87198 (78.11E, 49.80N, mb=5.8) recorded at CDSN station WMQ. Each trace is scaled by the peak amplitude. Note the relatively less P energy (with respect to Lg energy) in the Degelen event 87198 as compared to Shagan events of similar magnitudes.

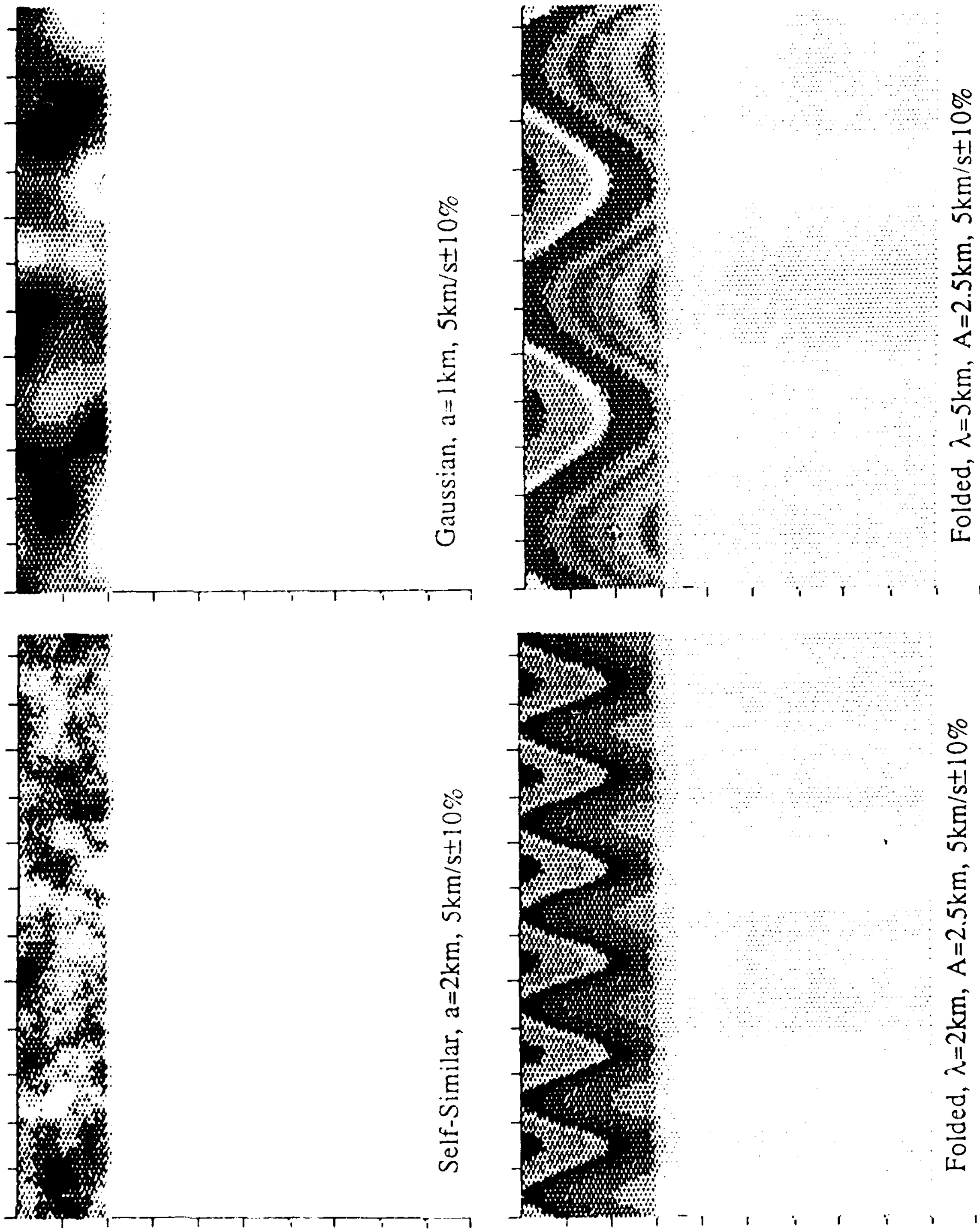

Gaussian, a=1km, 5km/s±10%
Folded, λ=5km, A=2.5km, 5km/s±10%
Self-Similar, a=2km, 5km/s±10%
Folded, λ=2km, A=2.5km, 5km/s±10%

Fig. 1

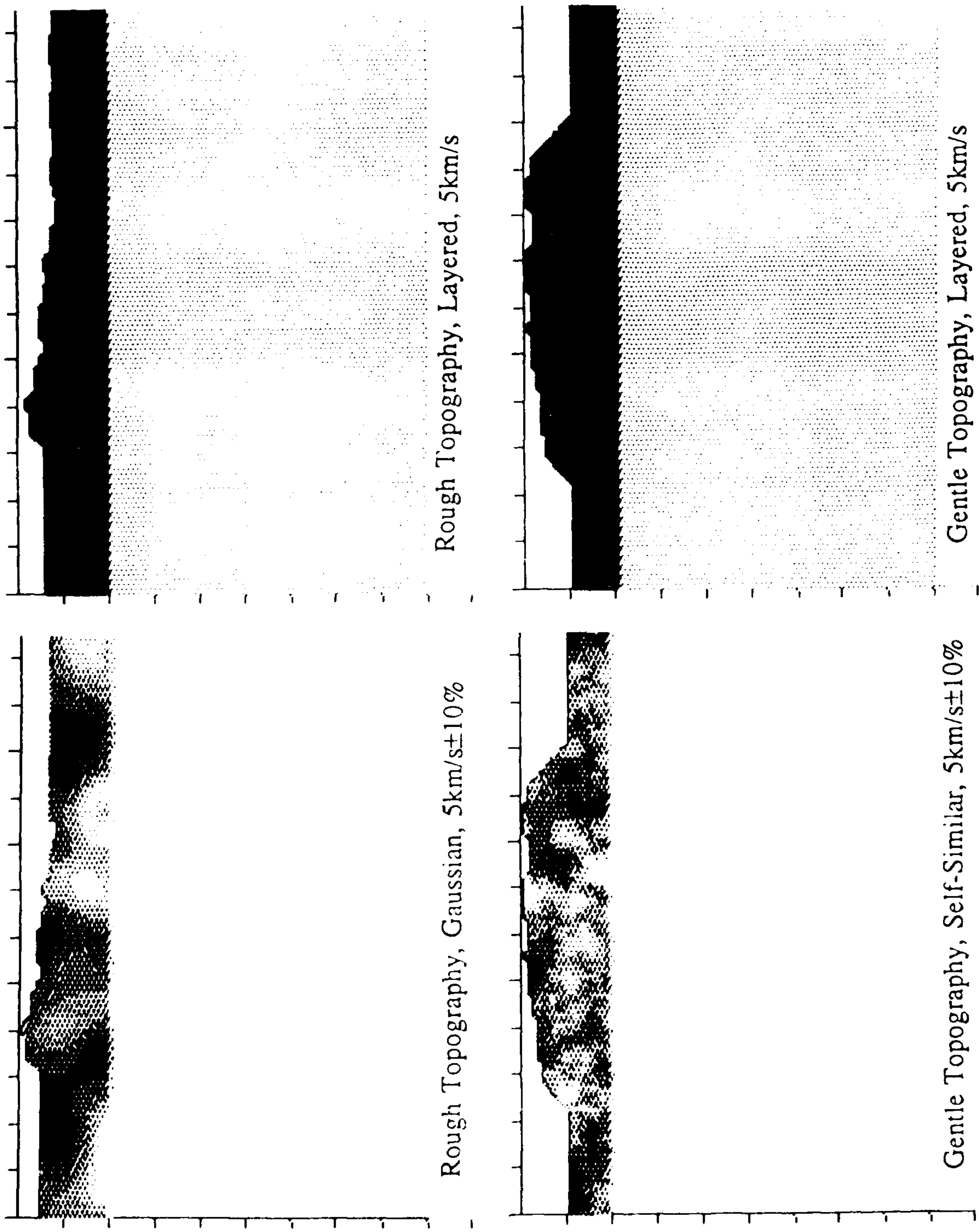
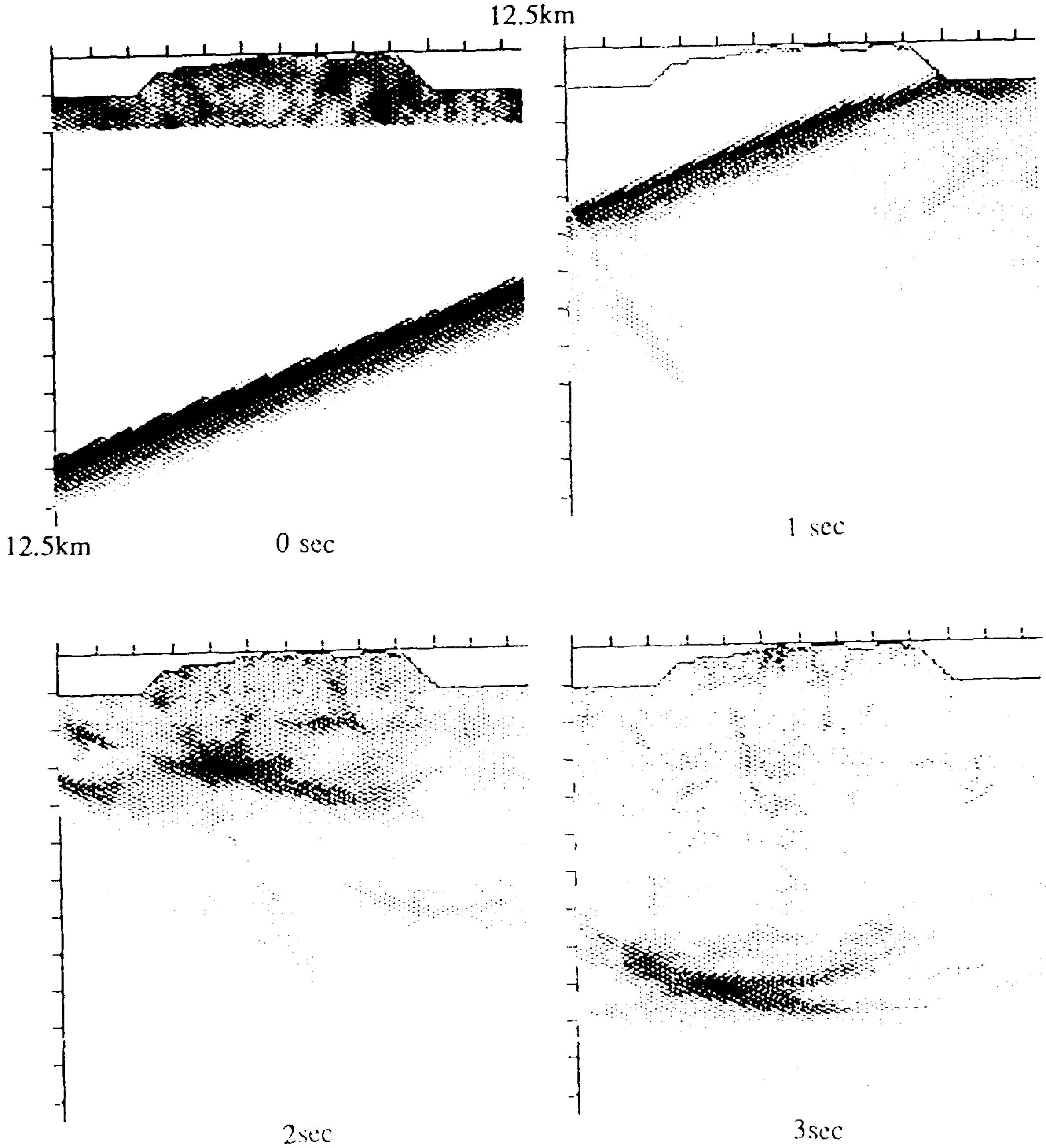
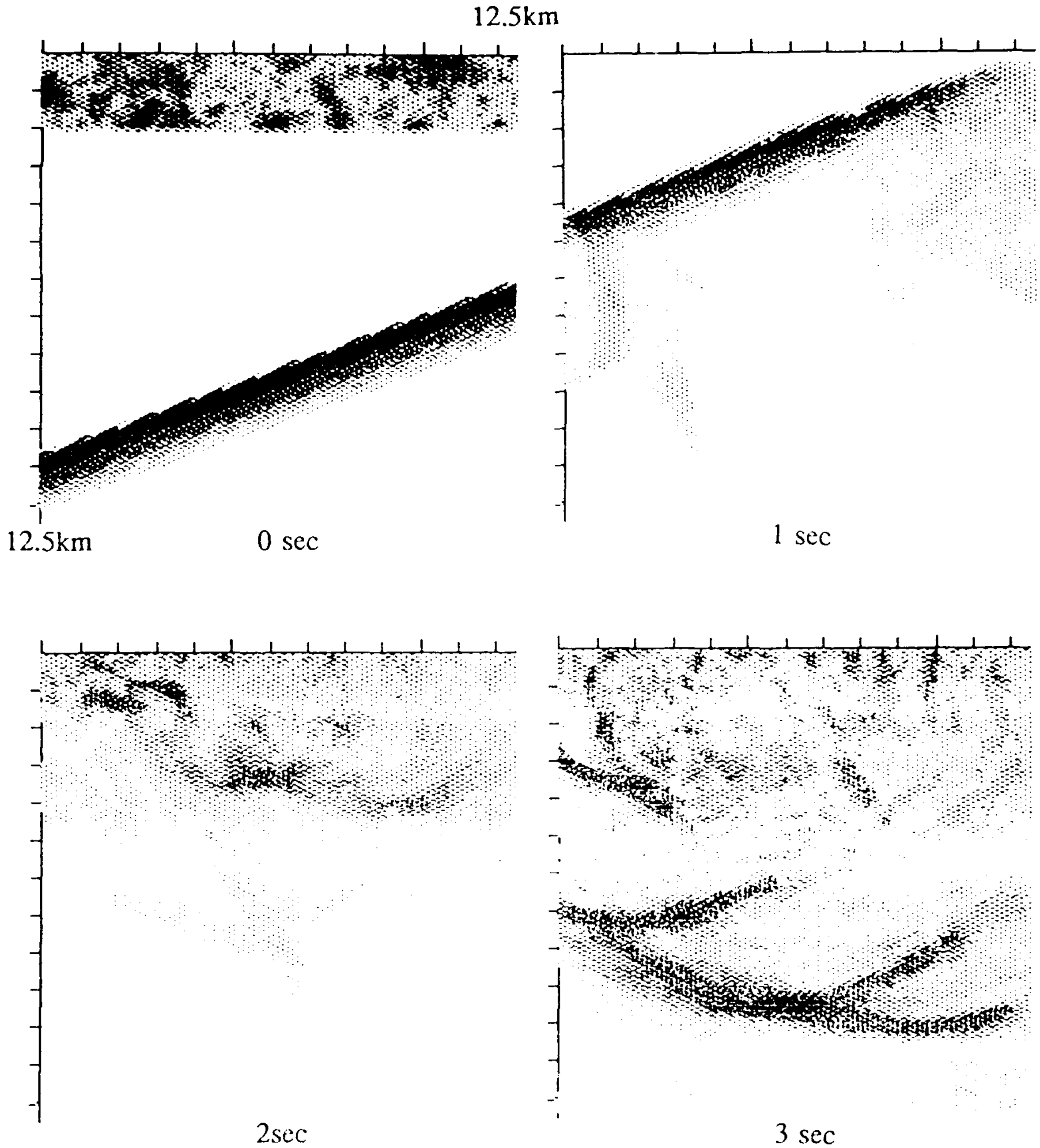

Rough Topography, Layered, 5km/s
Gentle Topography, Layered, 5km/s
Rough Topography, Gaussian, 5km/s±10%
Gentle Topography, Self-Similar, 5km/s±10%

Fig. 2



P wave, 20°

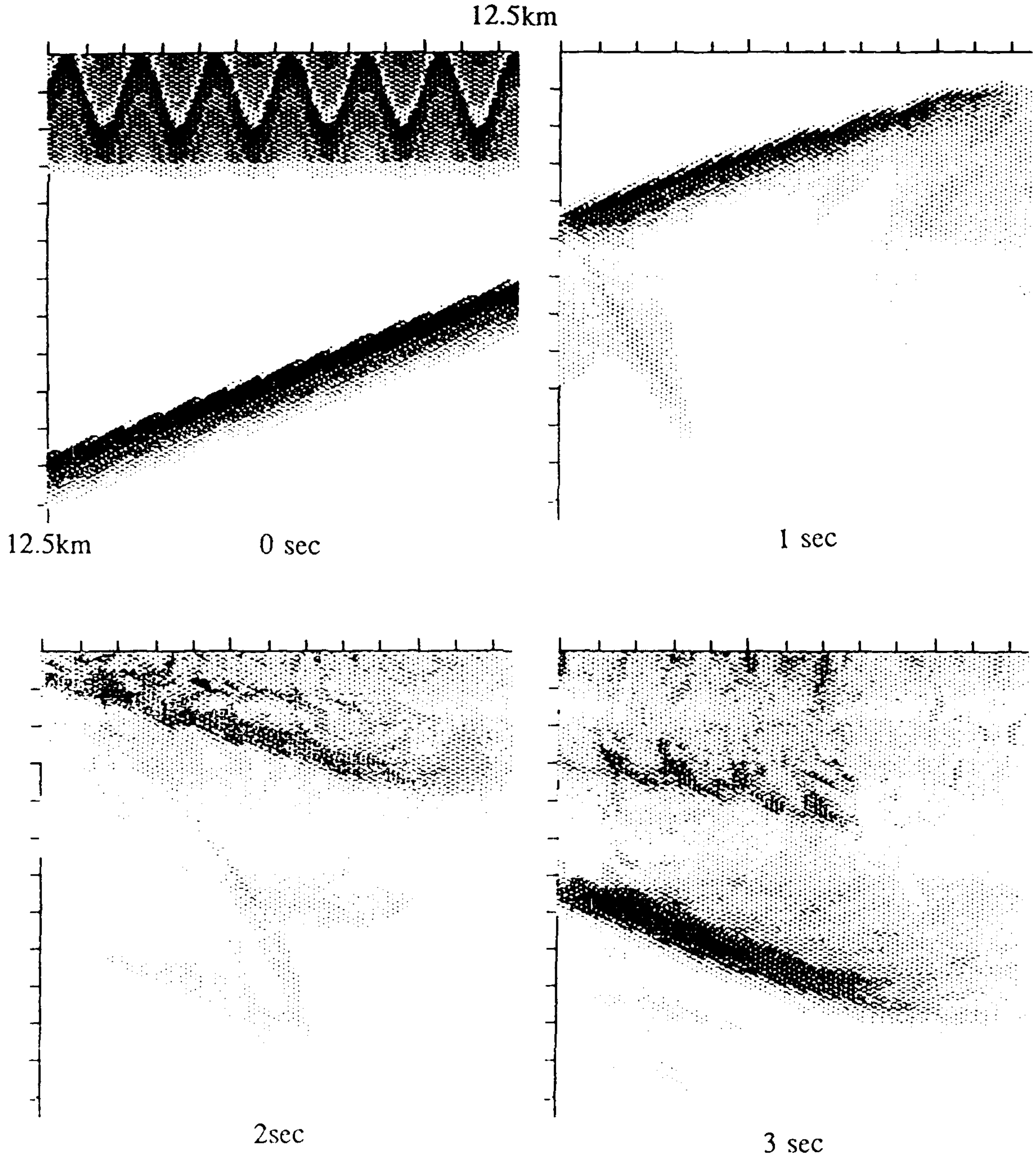
Self-Similar Model with Gentle Topography, 5km/s±10% Fig. 3



P wave, 20^o

Self-Similar Model, a=2km, 5km/s±20%

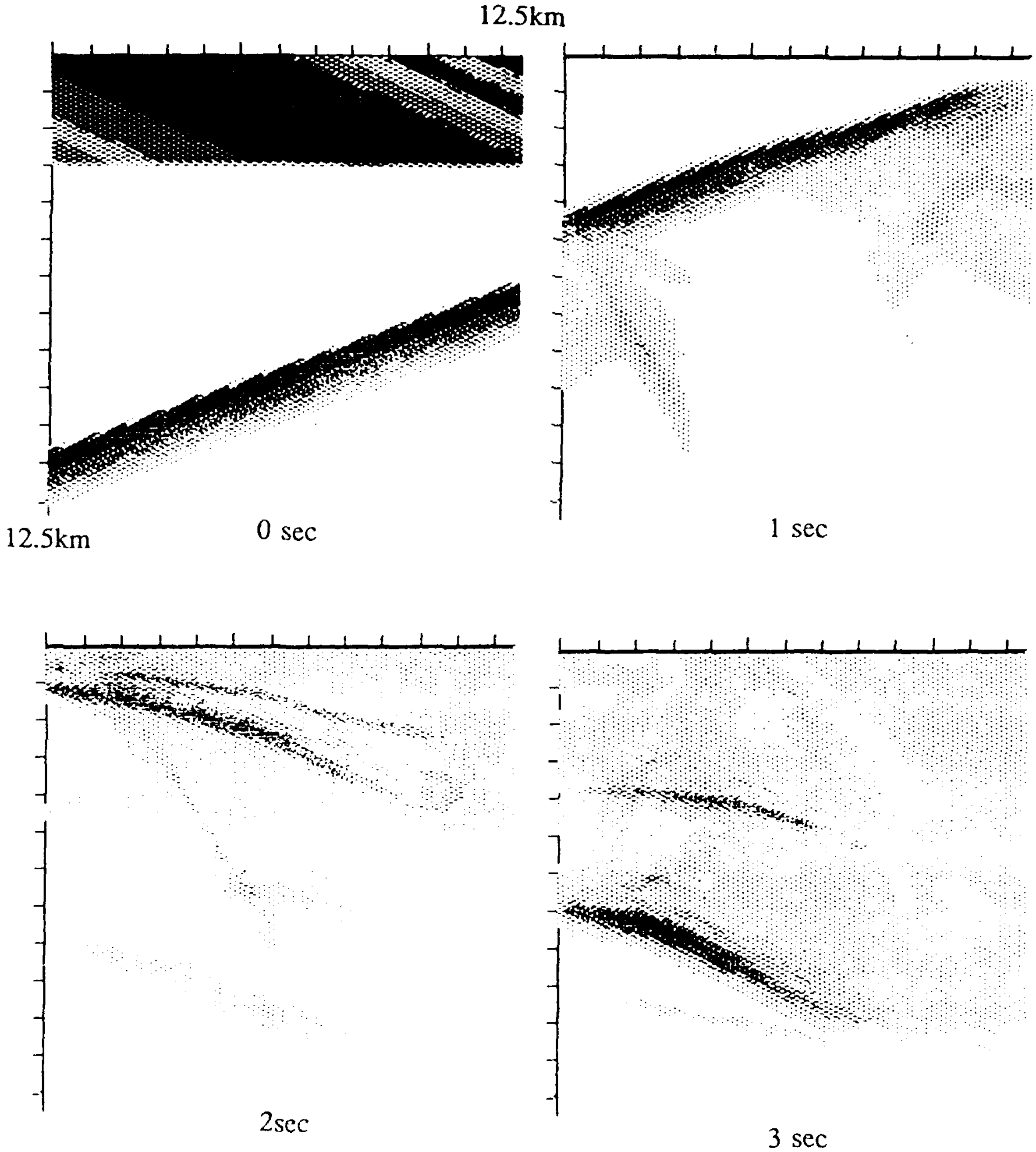
Fig. 4



P wave, 20^o

Folded Model, λ=3km, A=2.5km, 5km/s±10%

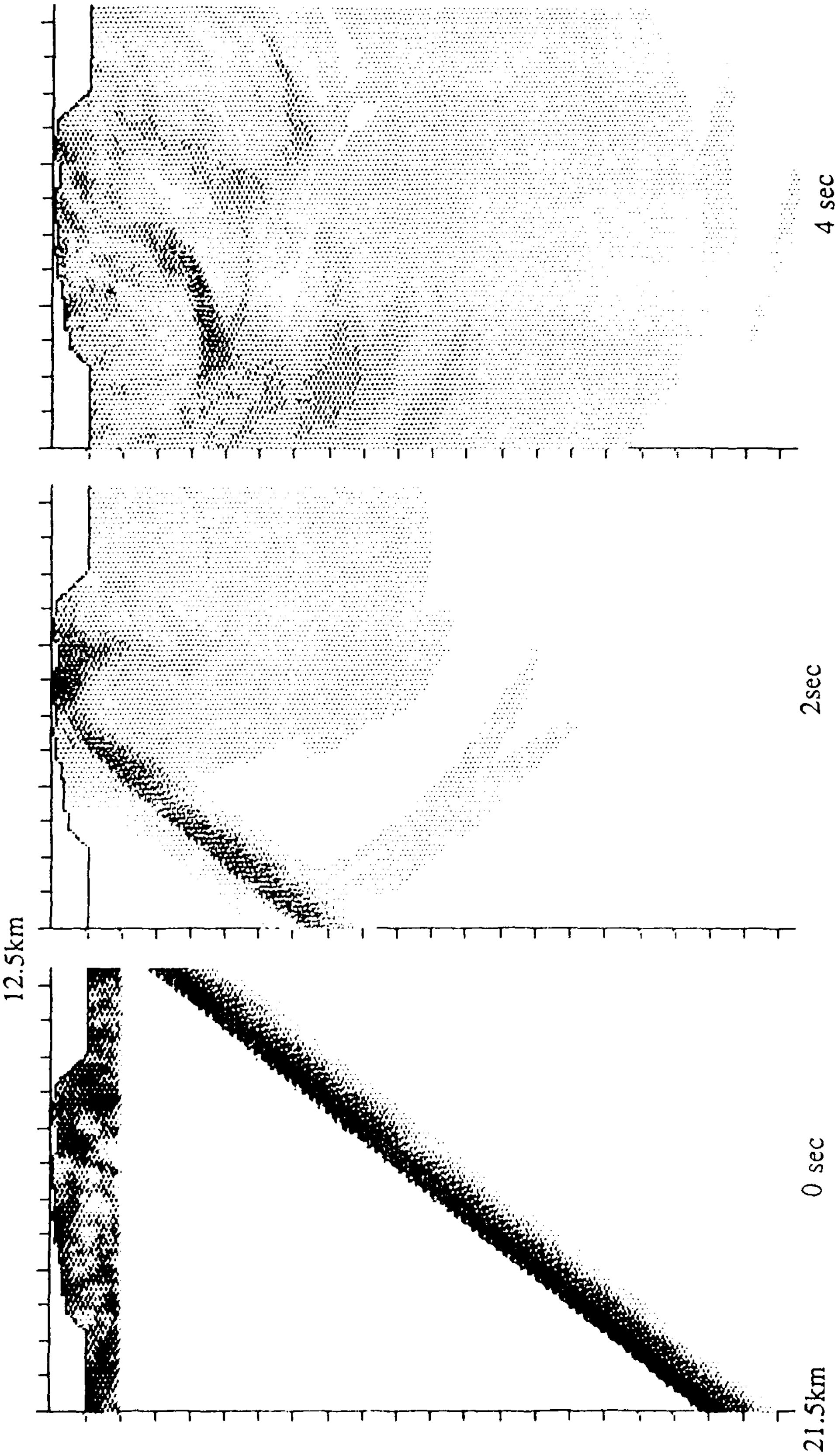
Fig. 5



P wave, 20°

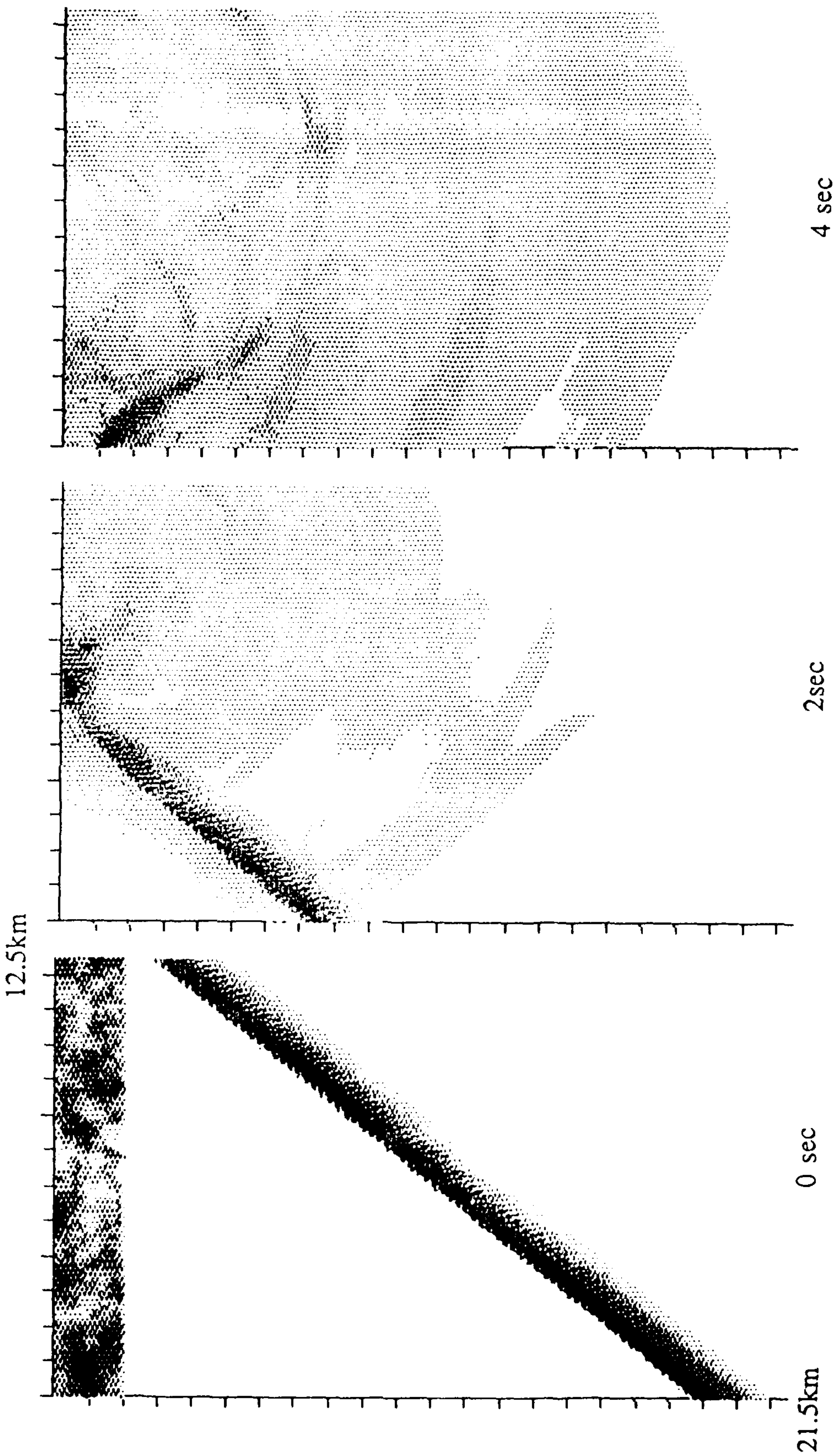
Gently Dipping Model, 5km/s±10%, –26°

Fig. 6



Self-Similar Model with Gentle Topography, 5km/s±10% SV wave, 52°

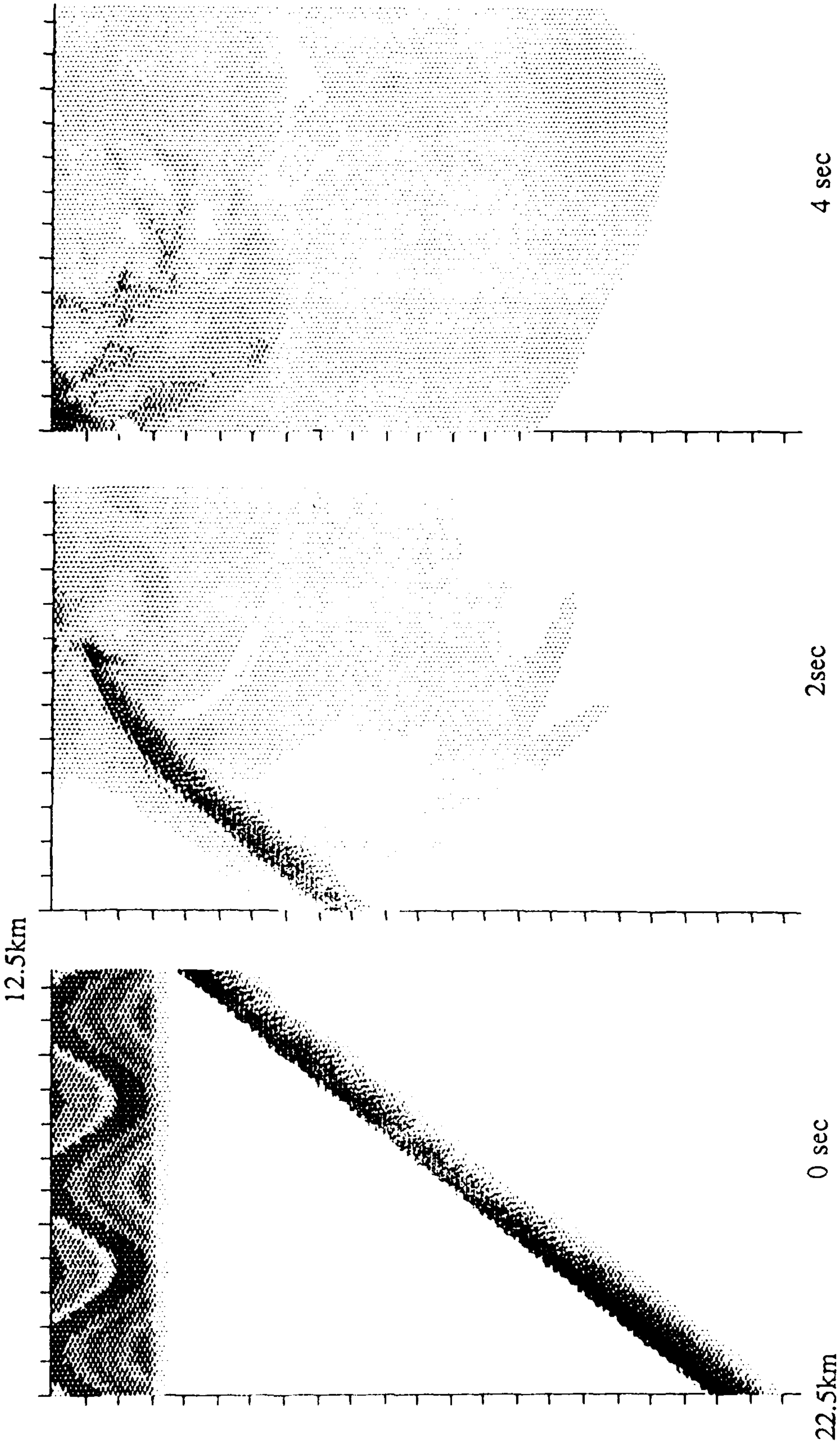
Fig. 7



SV wave, 52°

Self-Similar Model, a=2km, 5km/s±10%

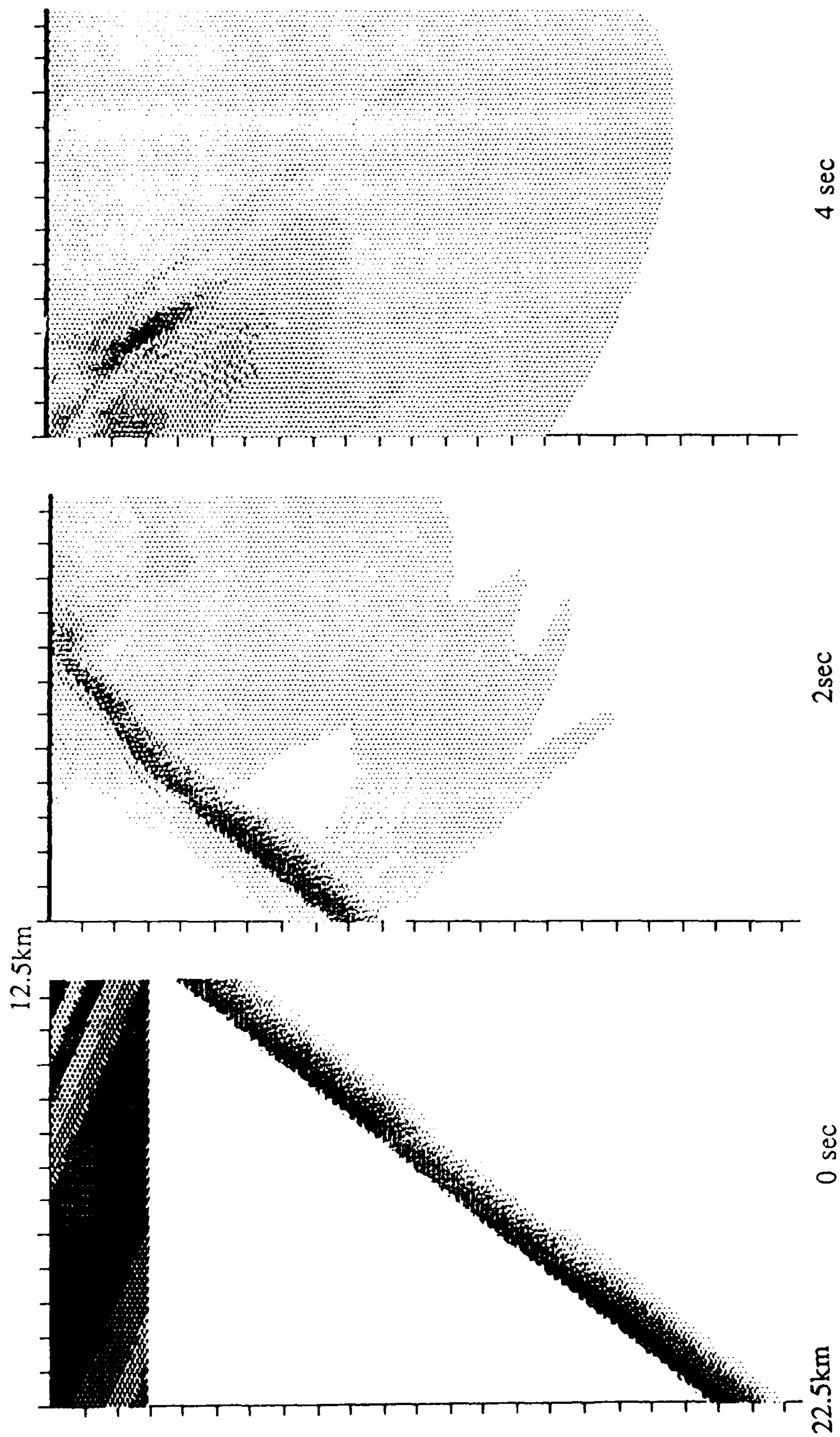
Fig. 8



SV wave, 52^o

Folded Model, λ=5km, A=2.5km, 5km/s±10%

Fig. 9



SV wave, 52°

Gently Dipping Model, 5km/s±10%, −26°

Fig. 10

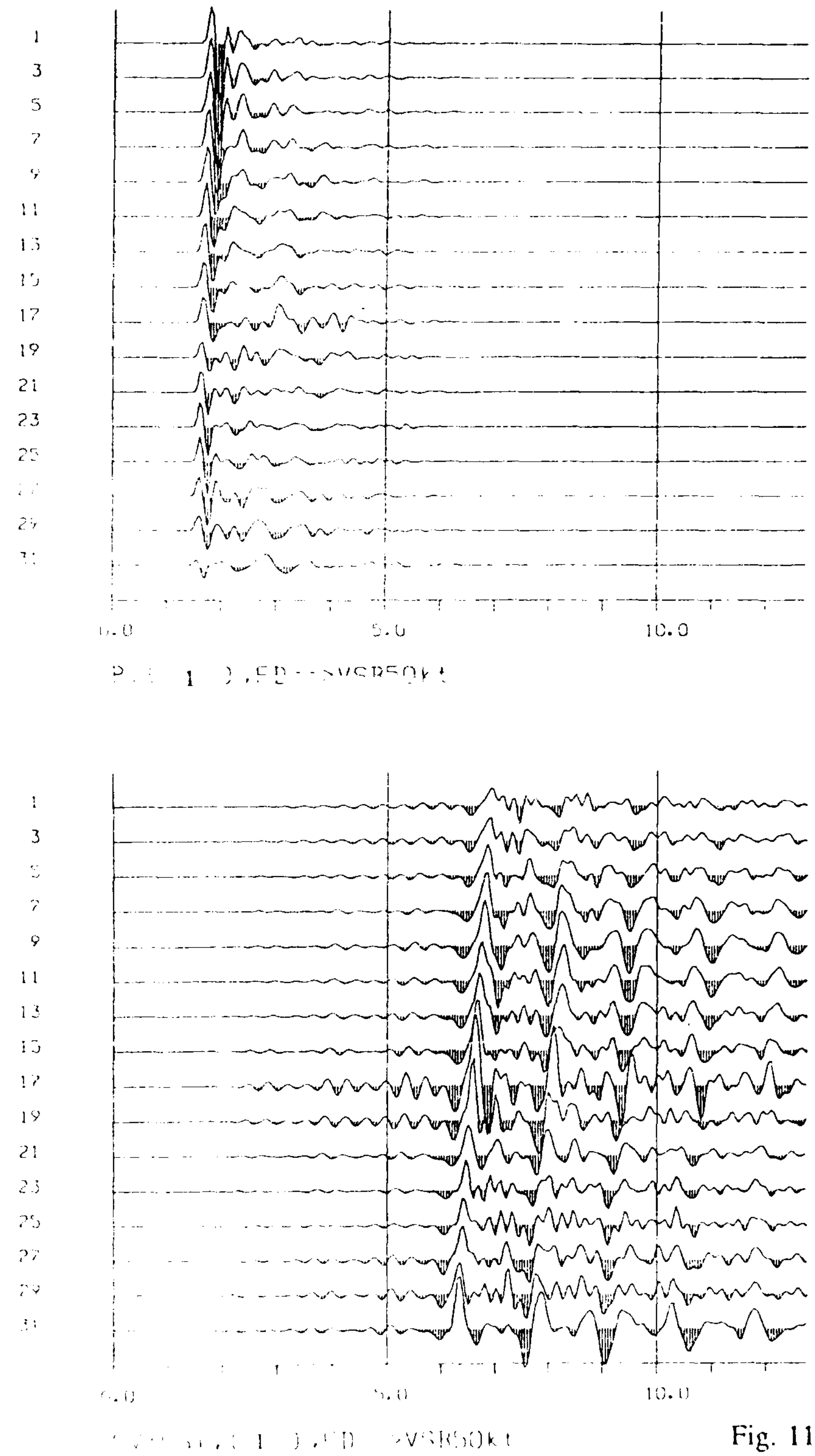


Fig. 11

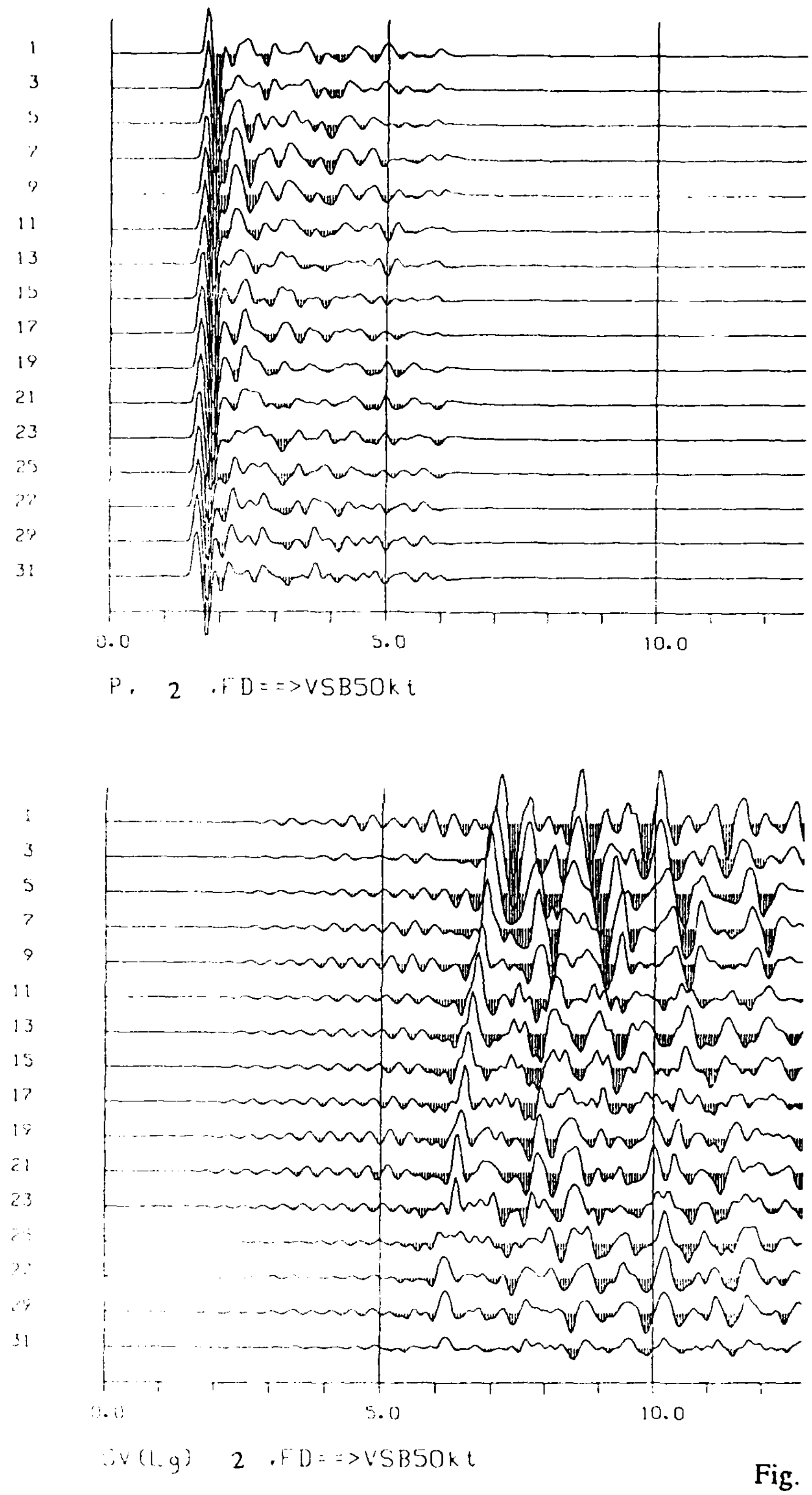

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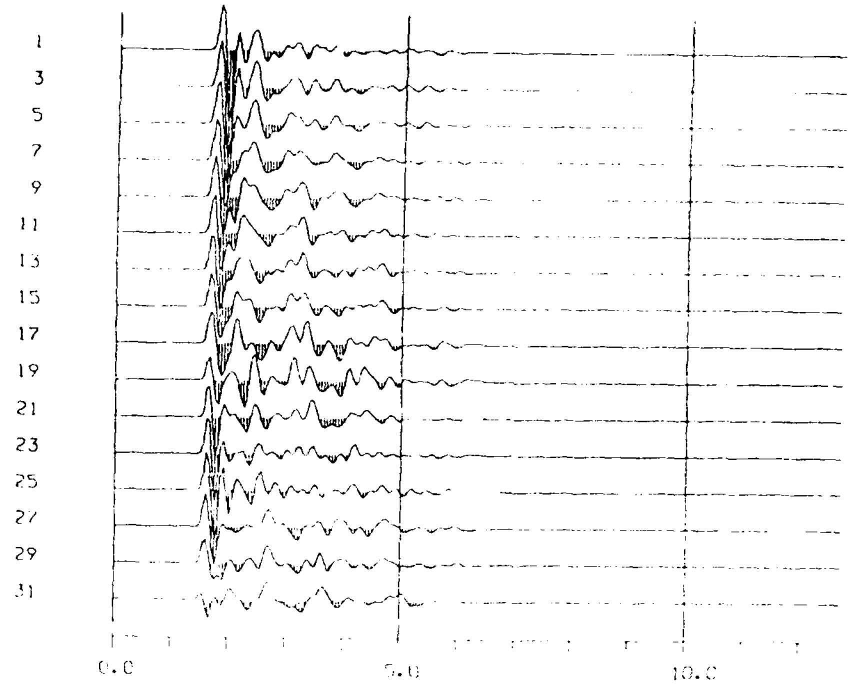
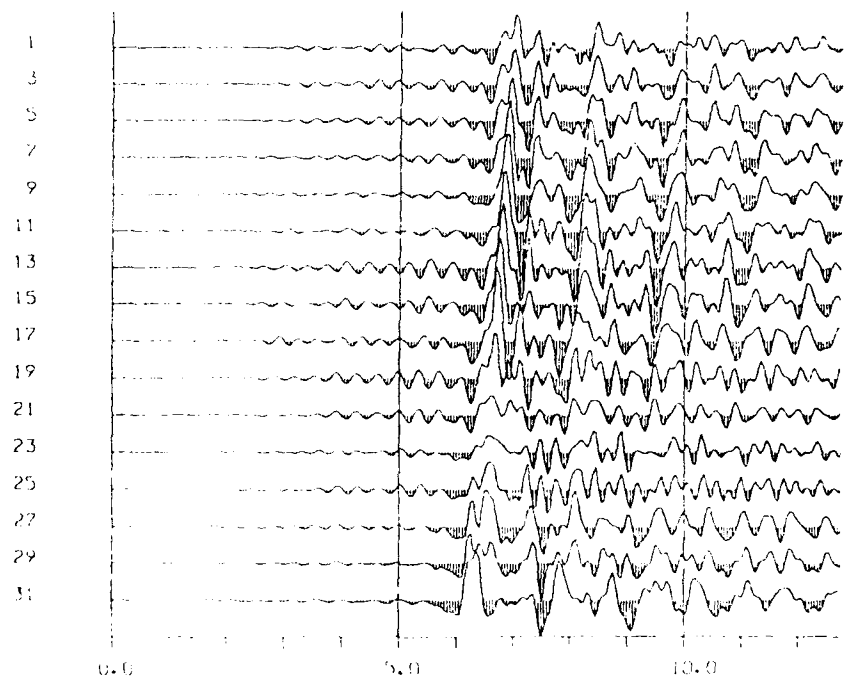
Fig. 12

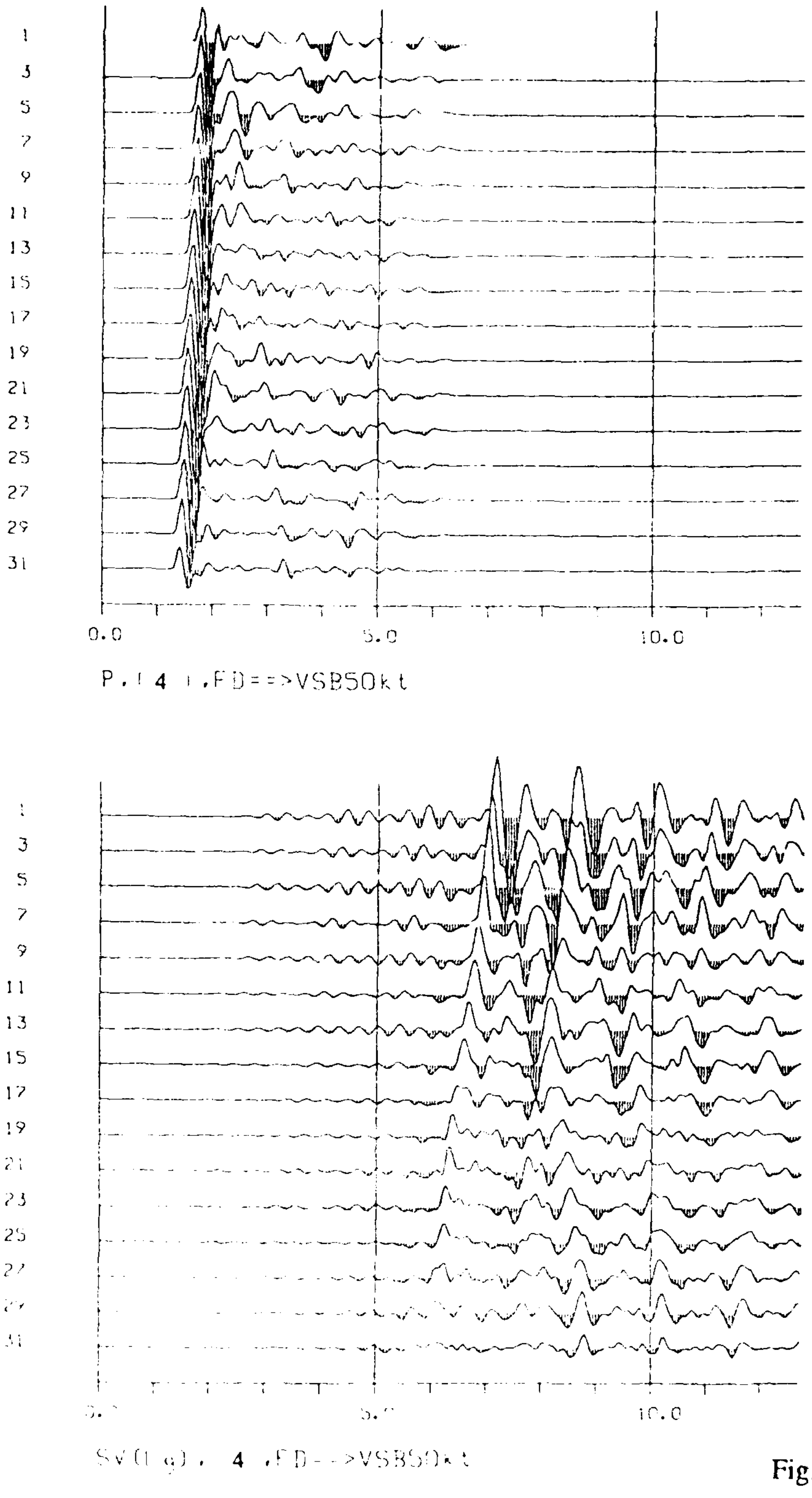


P, 3 .FD SVSB50kt



SV(Lg) 3 -D- SVSB50kt

Fig. 13



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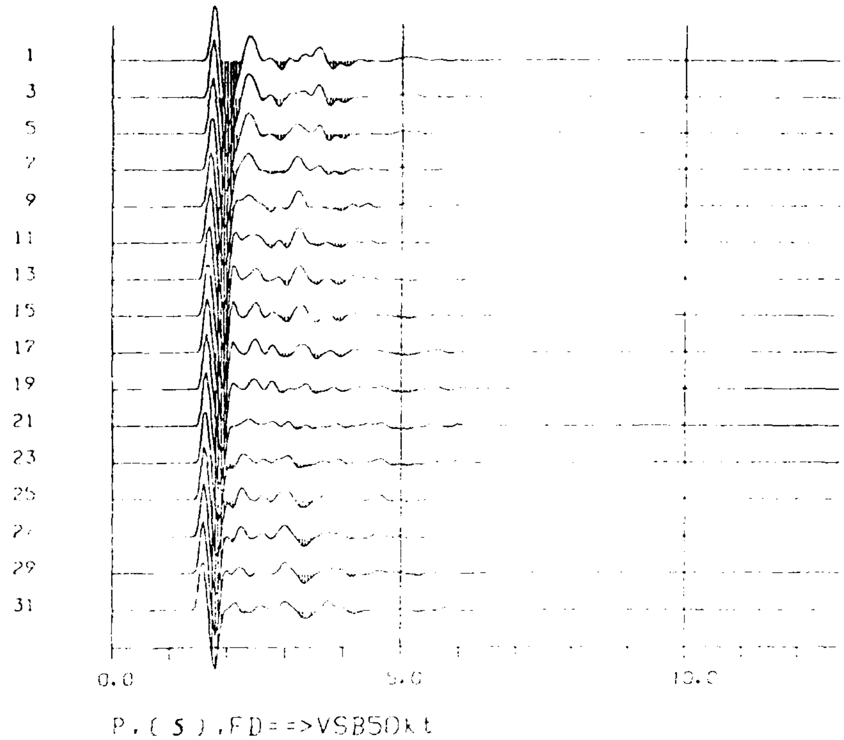
SV(Lg), 4 ,FD==>VSB50kt

Fig. 14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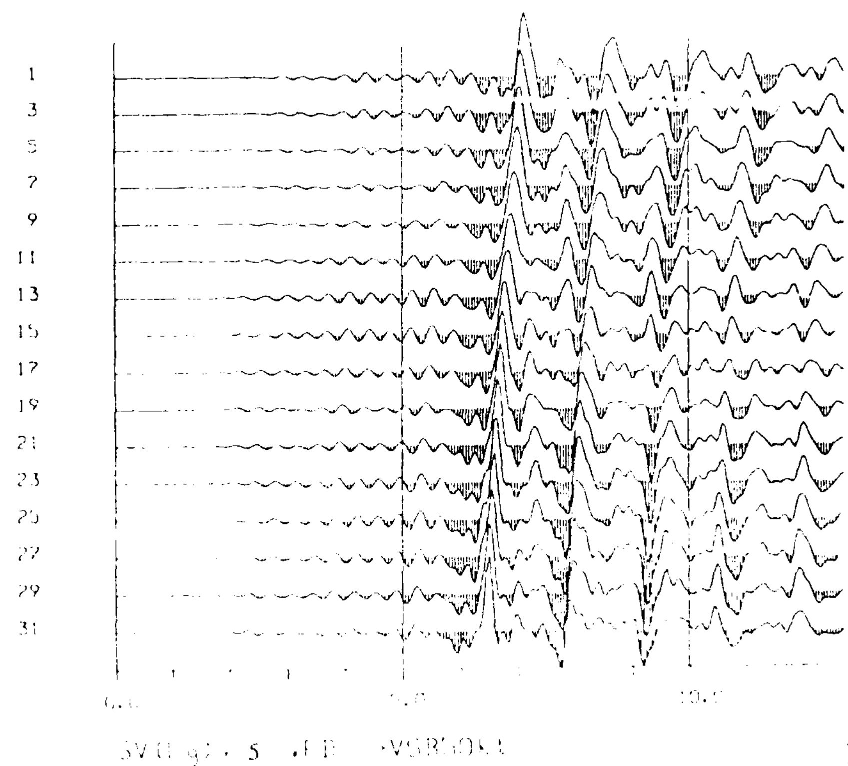
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Fig. 15

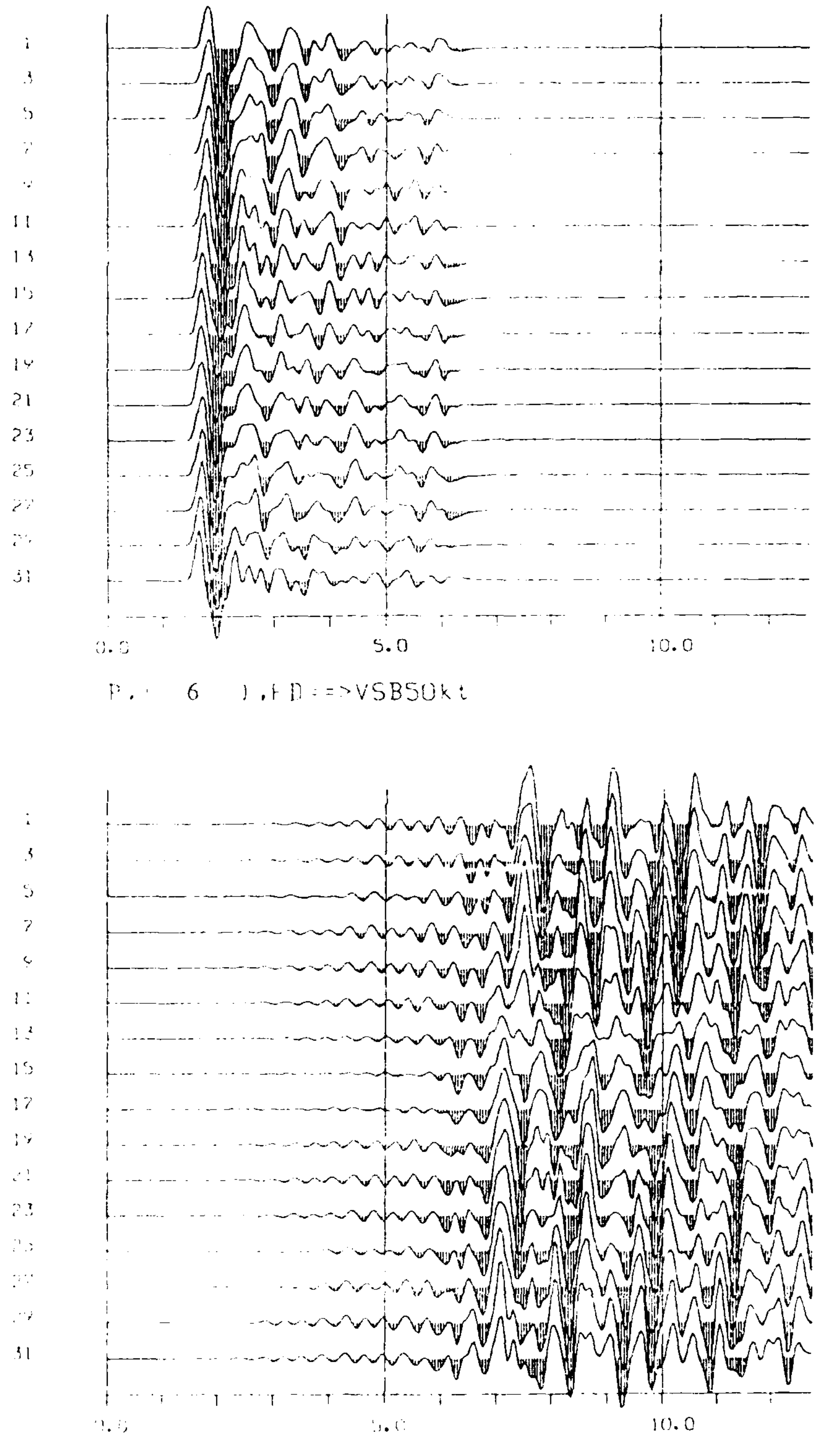


Fig. 16

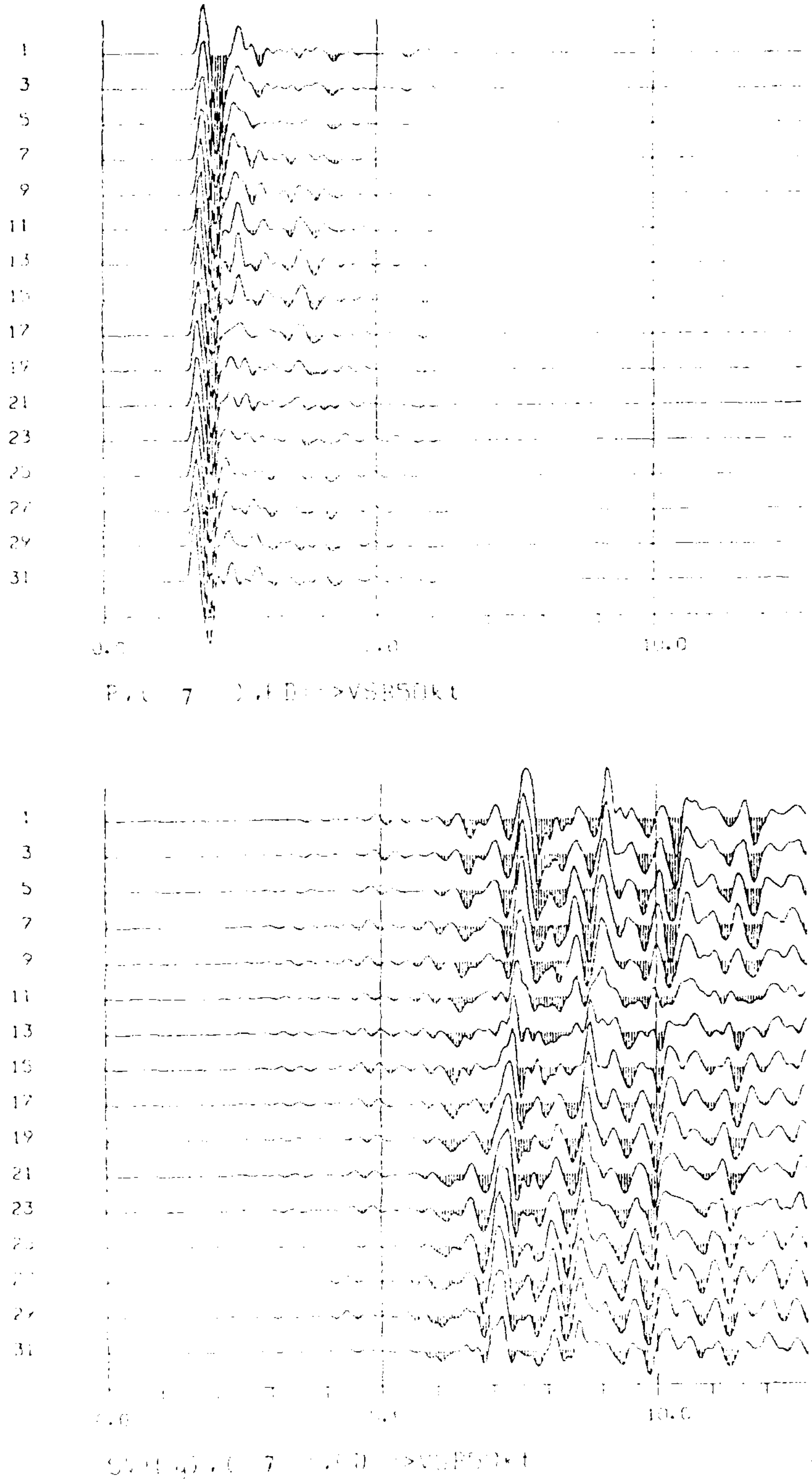


Fig. 17

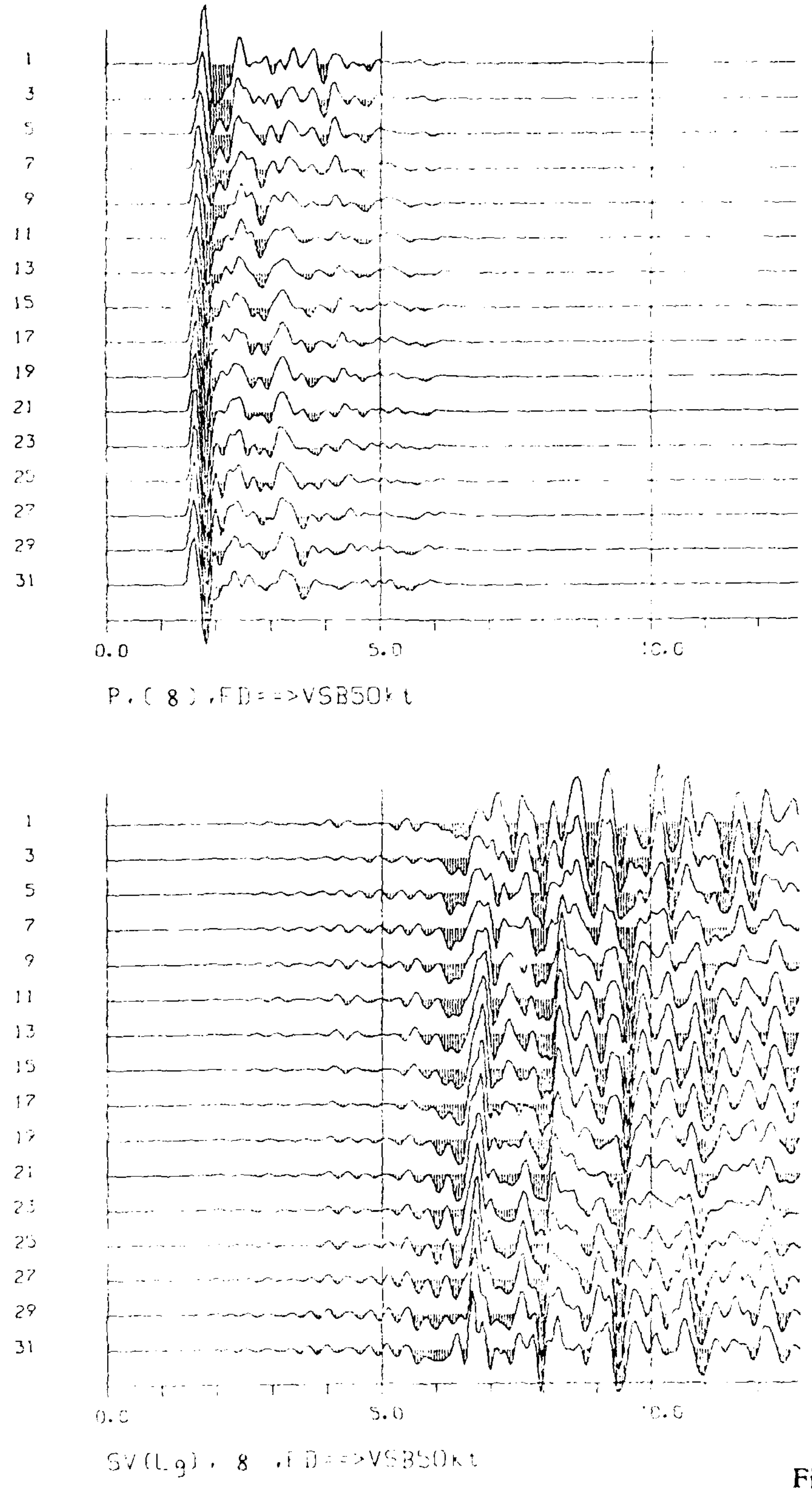
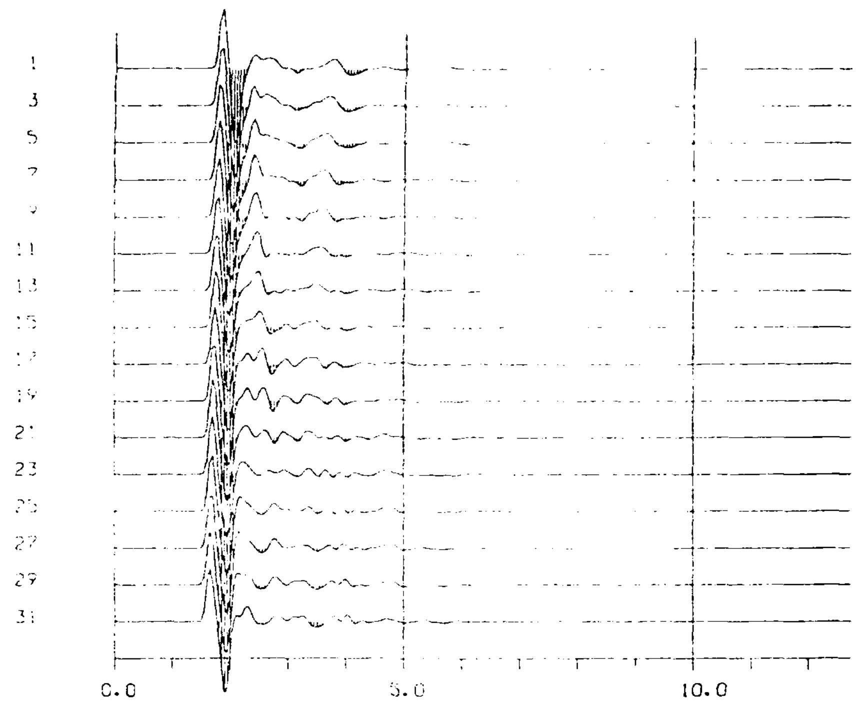
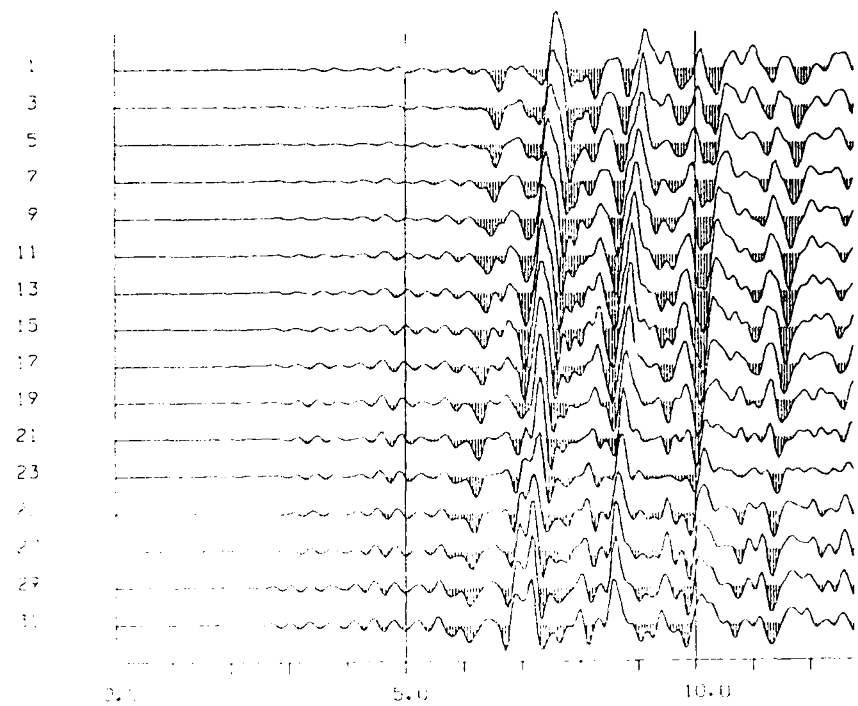


Fig. 18



P, (9), FD==>VSB50kt



SV(Lg), 9 , FD==>VSB50kt

Fig. 19

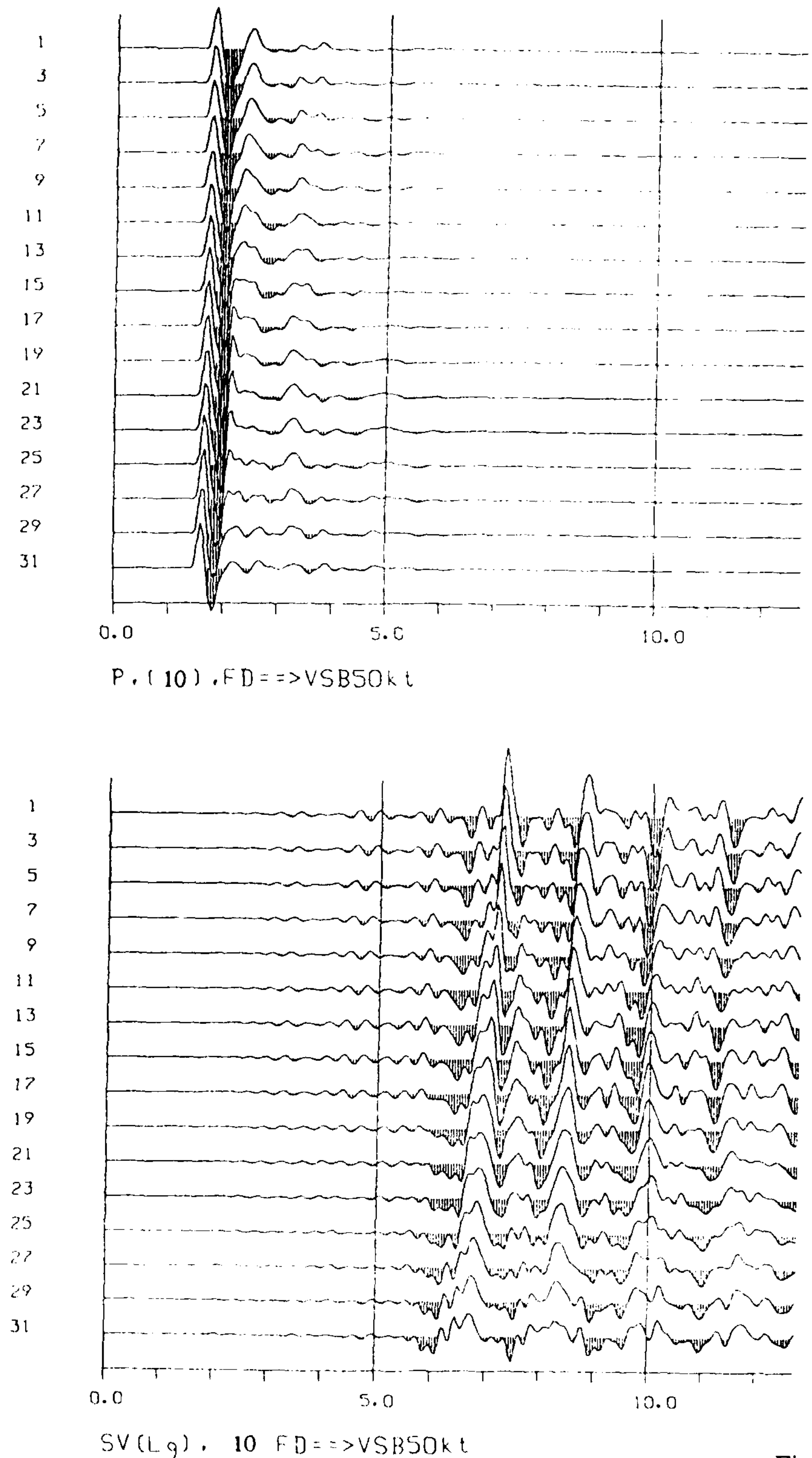


Fig. 20

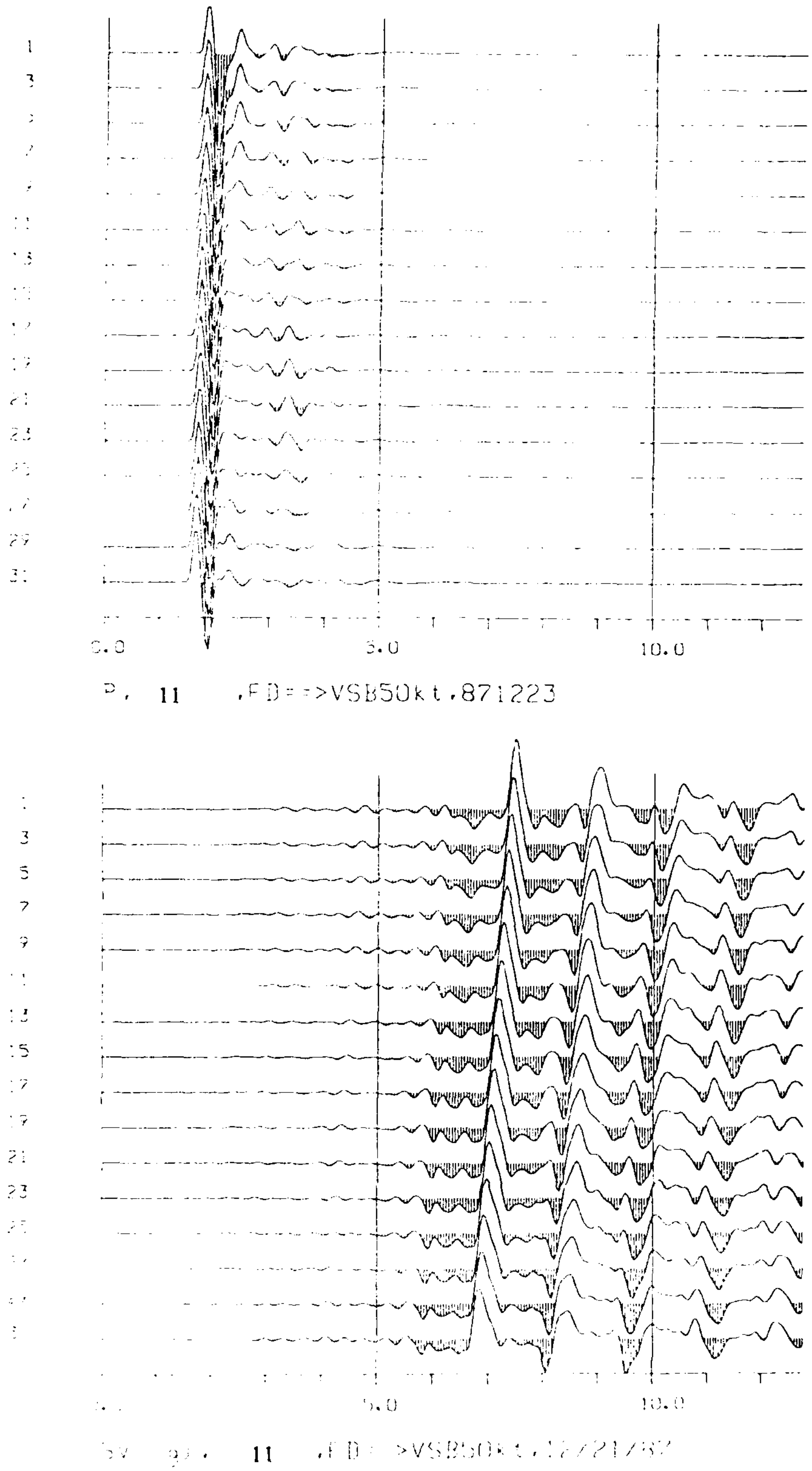


Fig. 21

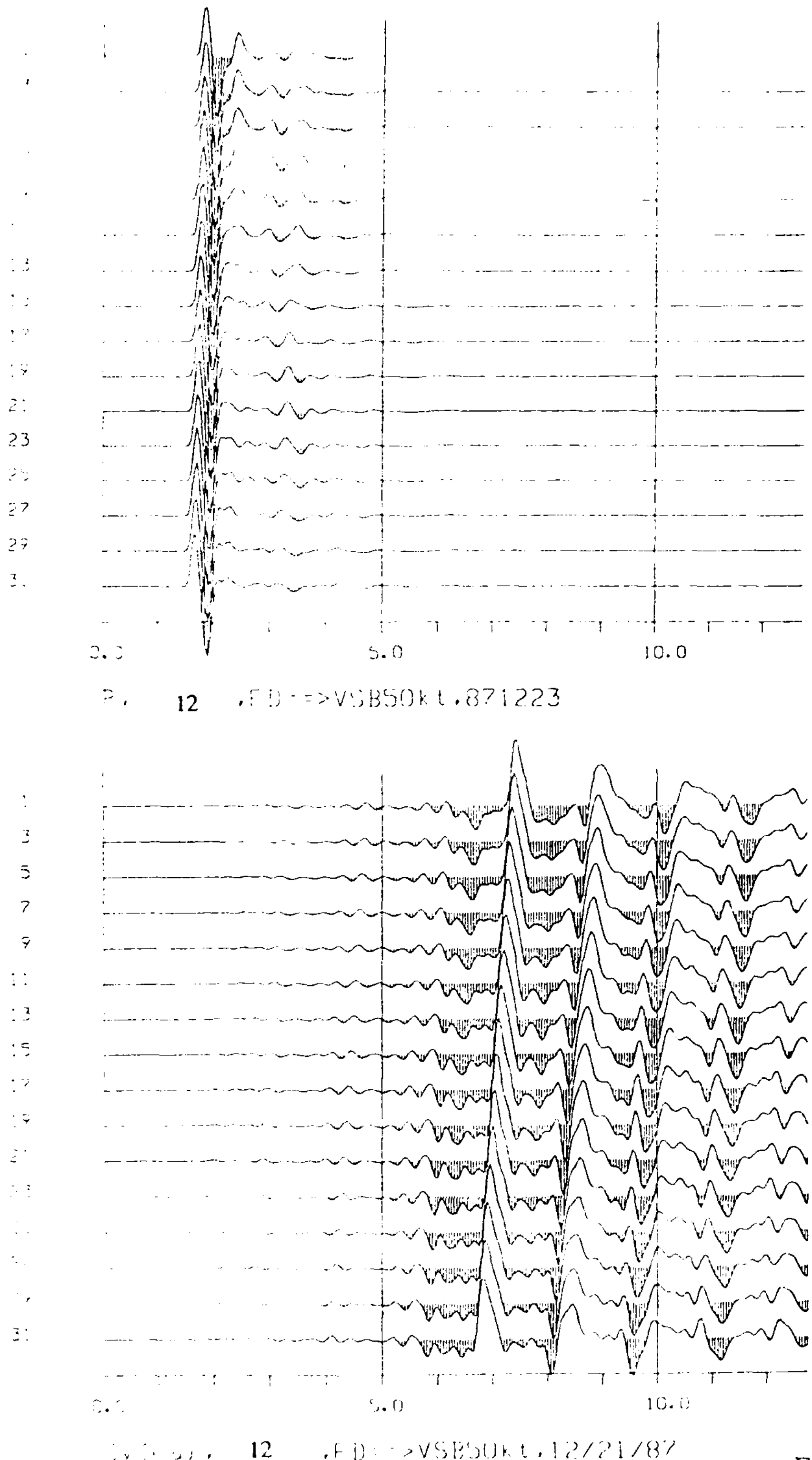


Fig. 22

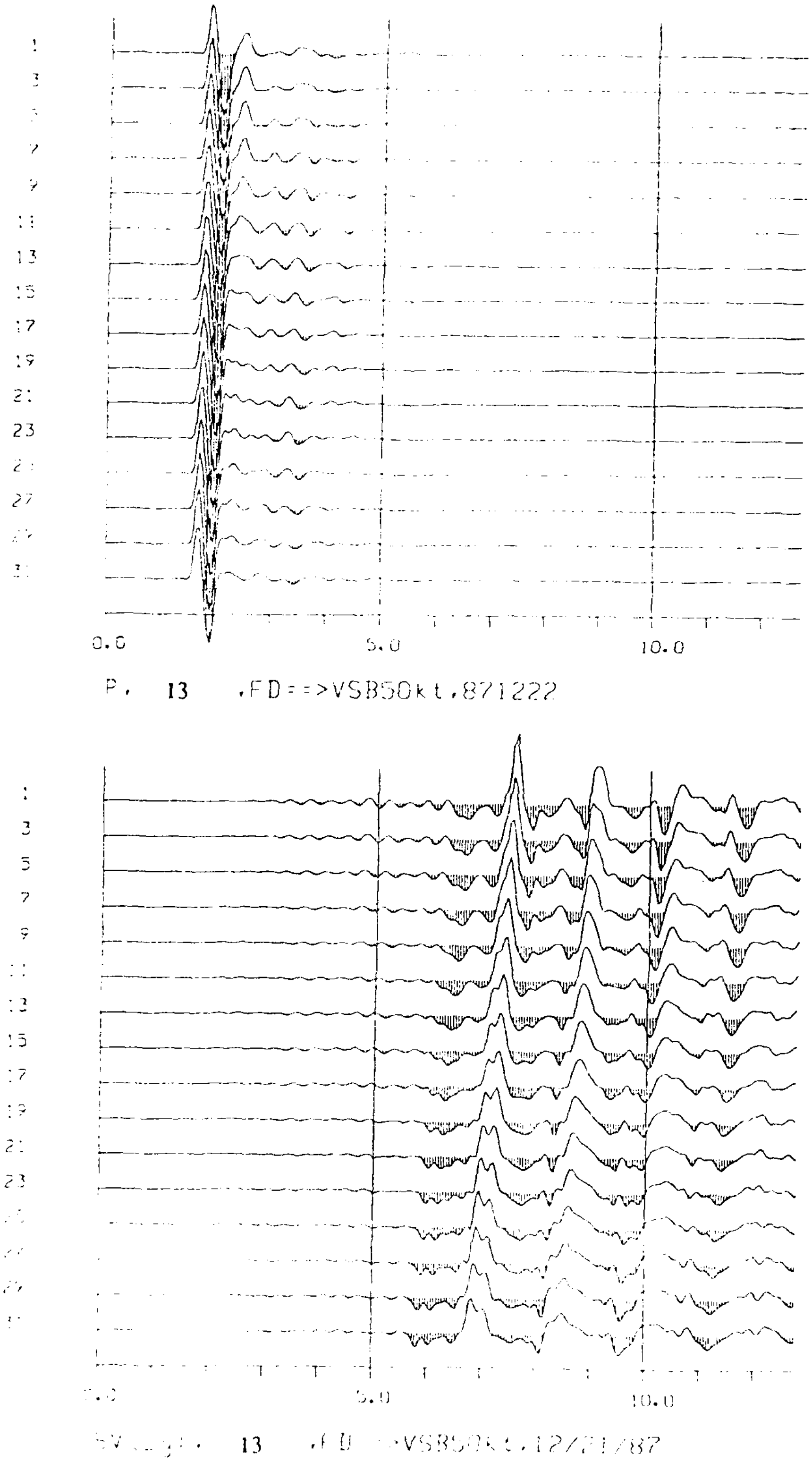
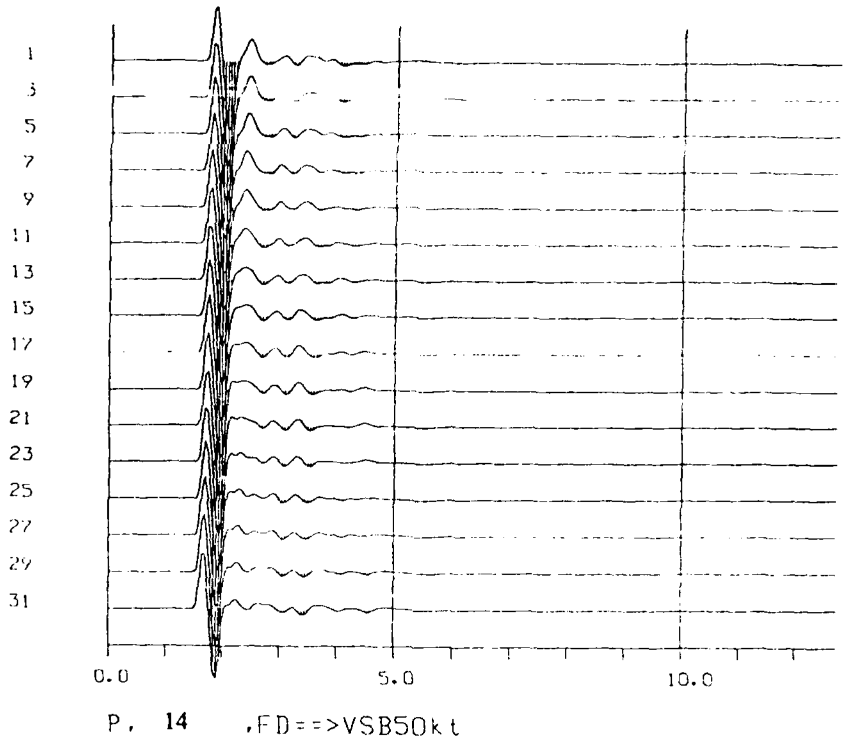


Fig. 23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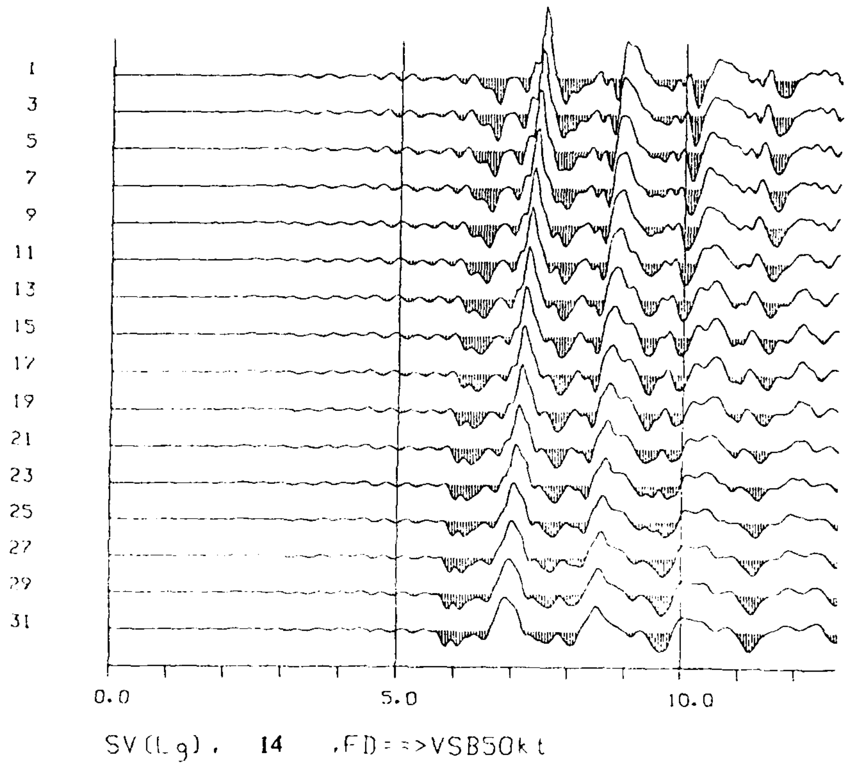
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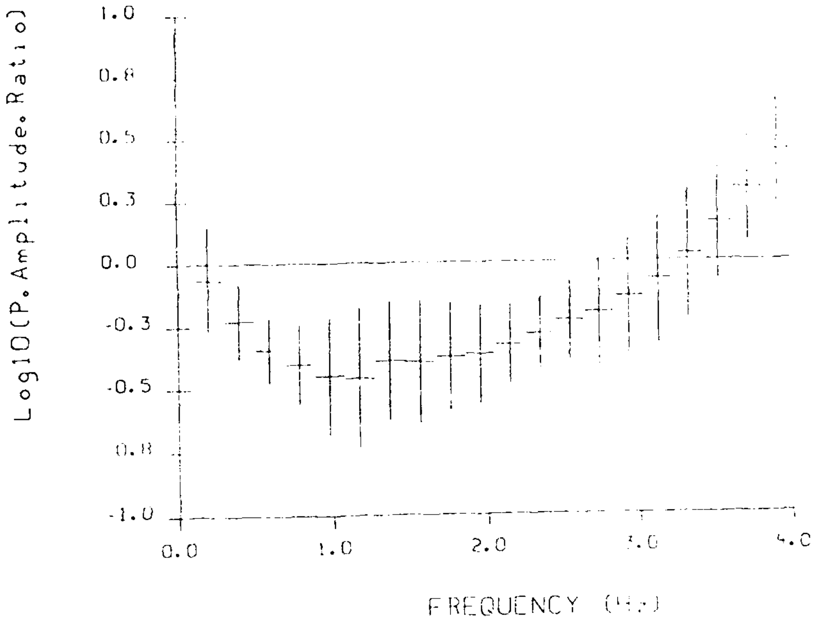
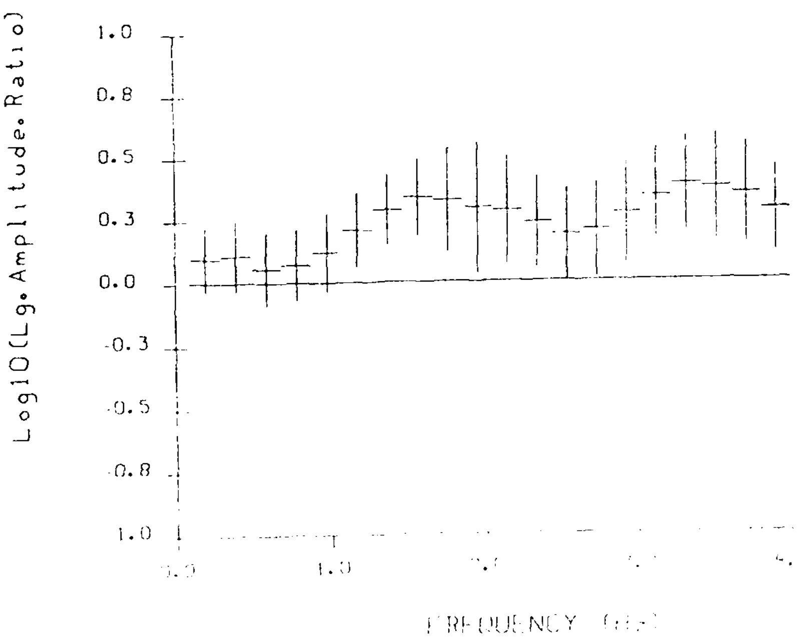
SV(Lg), 14 ,FD==>VSB50kt

Fig. 24

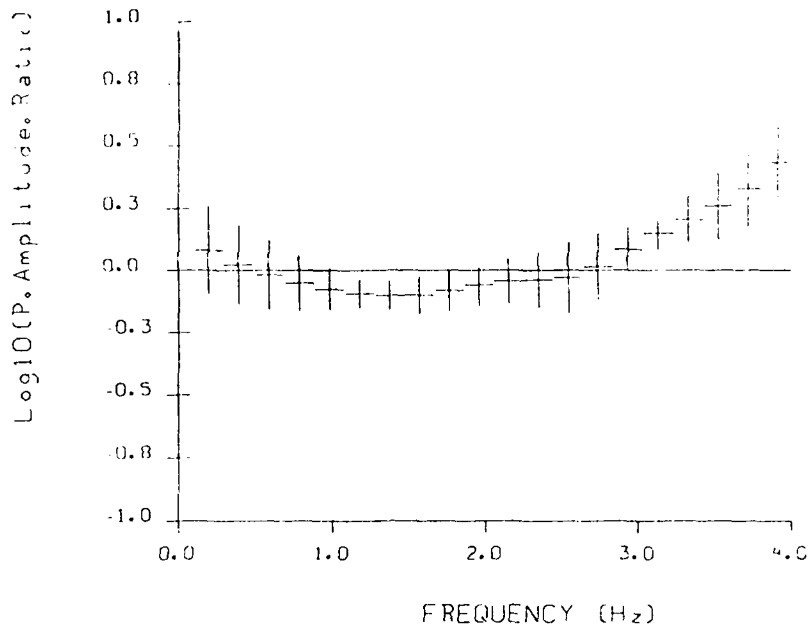


P(1)/P(5+0%,2km,flat)

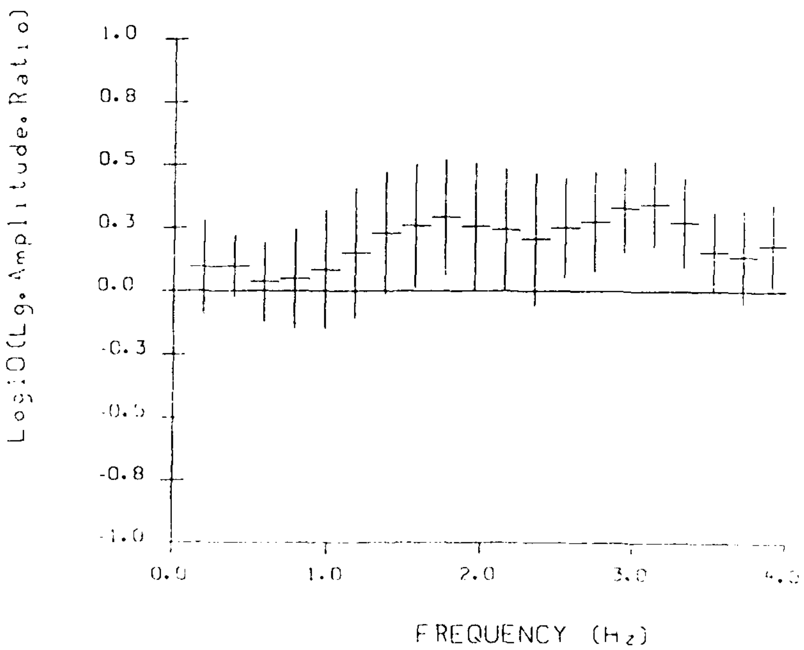


Lg(1)/Lg(5+0%,2km,flat)

Fig. 25

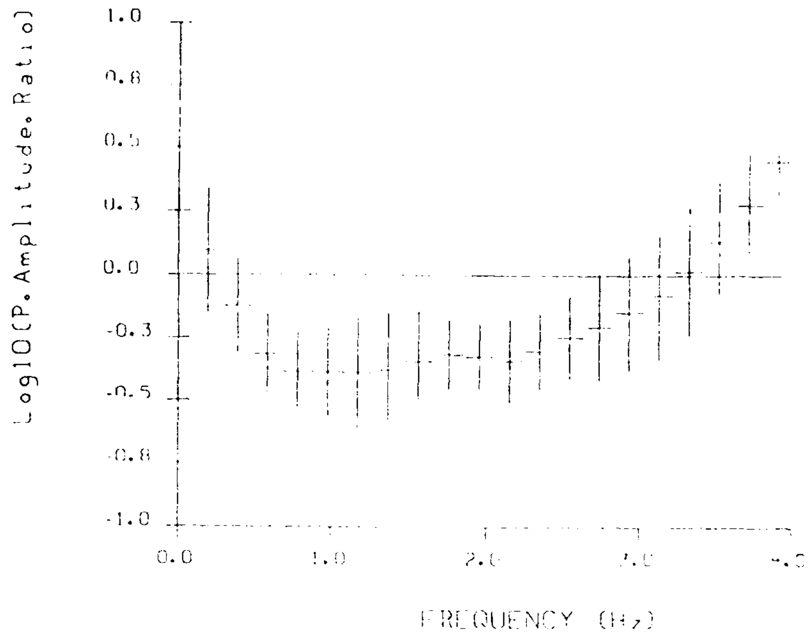


P 2 /P(5+0%,2km,flat)



Lg 2 /Lg(5+0%,2km,flat)

Fig. 26



P 3 /P(5+0%,2km,flat)

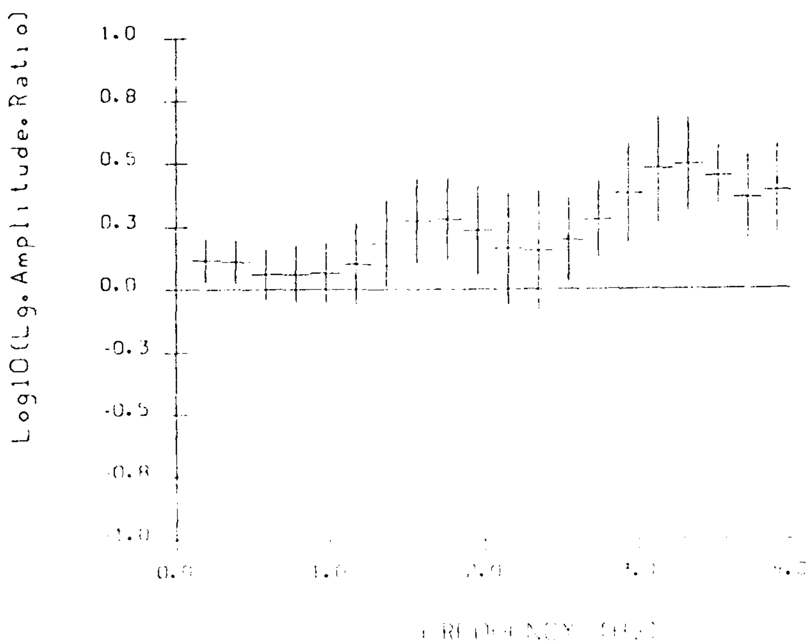
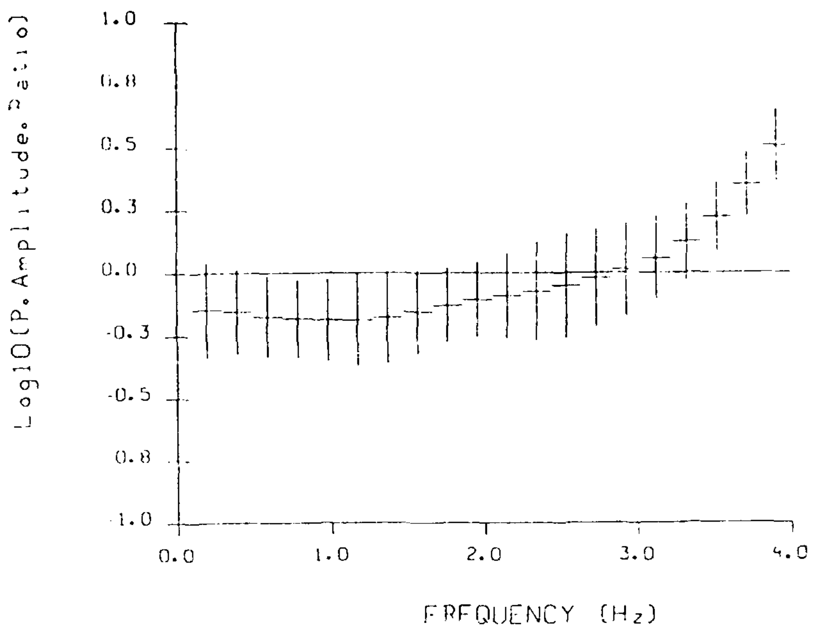
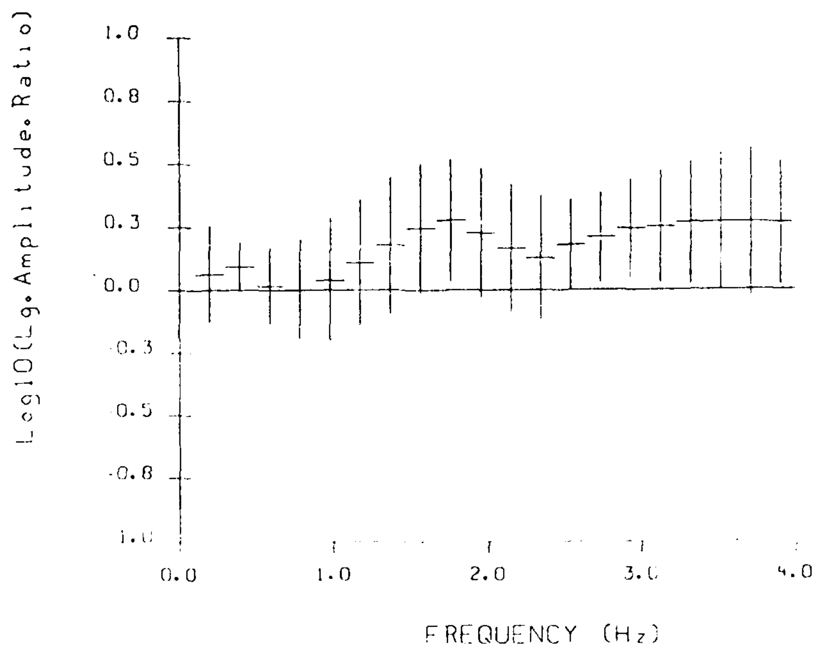


Fig. 27

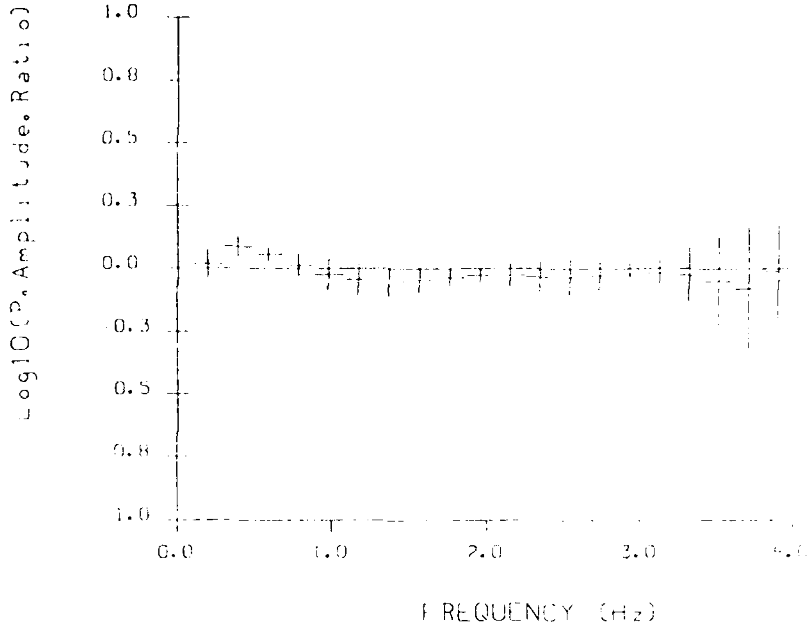


P(4)/P(5+0%,2km,flat)



Lg 4 /Lg(5+0%,2km,flat)

Fig. 28



P(5)/P(5+0%,2km,flat)

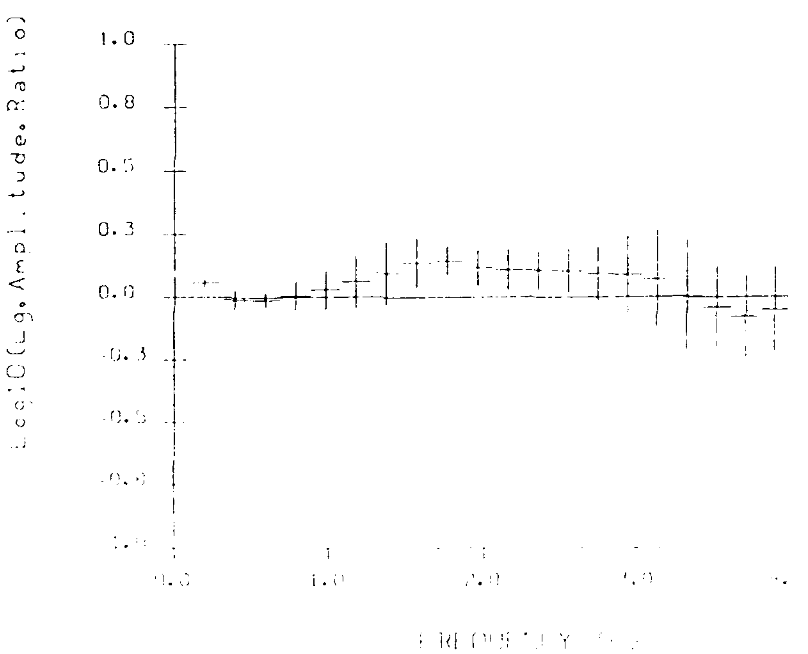
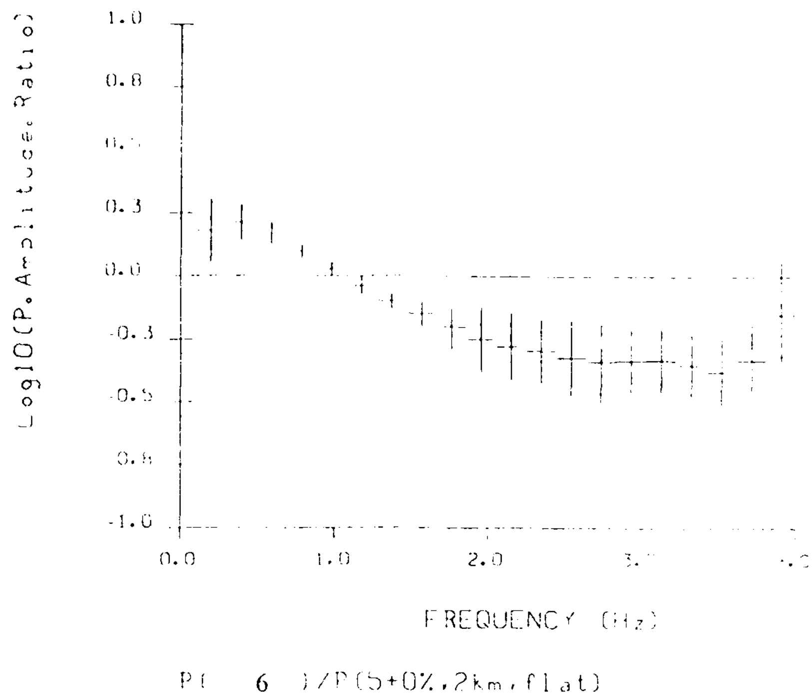


Fig. 29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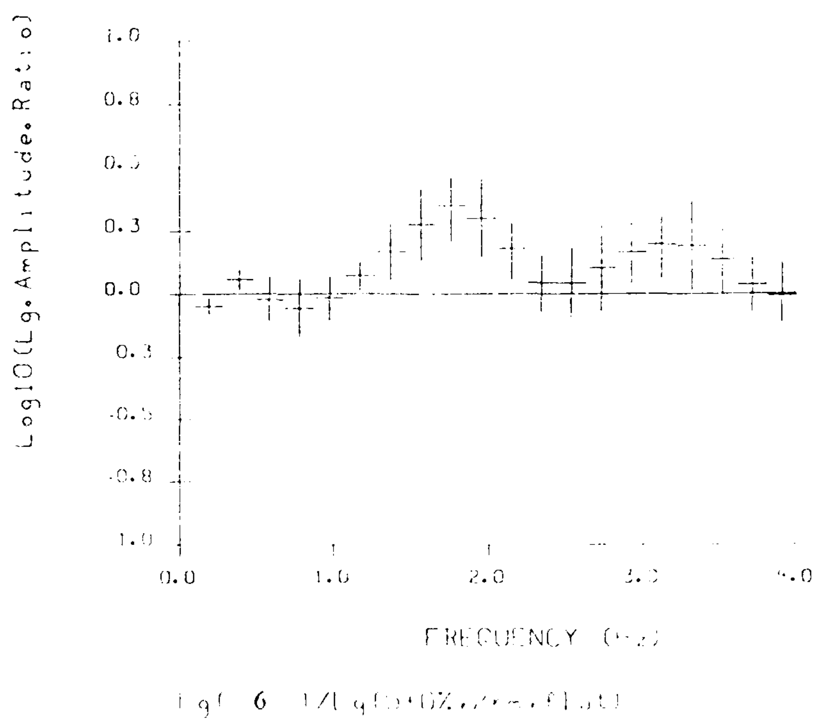
0.0
-0.3
-0.5
-1.0
0.0
1.0
2.0
FREQUENCY (Hz)


Log10(Lg. Amplitude. Ratio)
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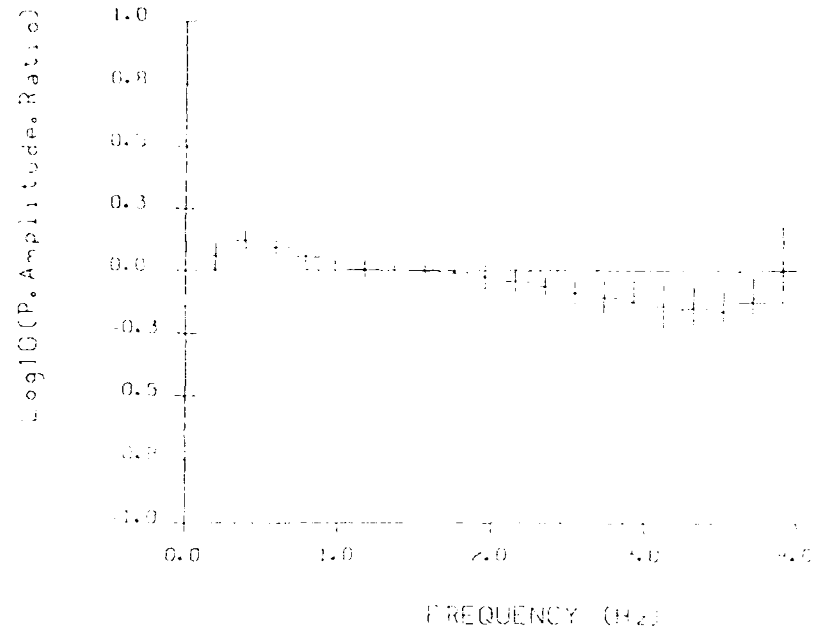
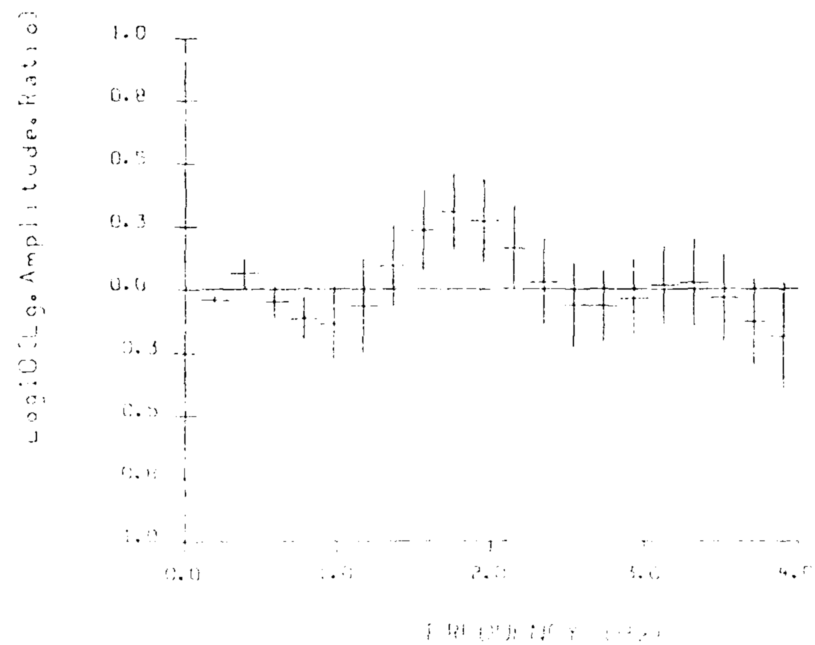
0.3
0.0
-0.5
-0.8
0.0
1.0
2.0
FREQUENCY

Fig. 30

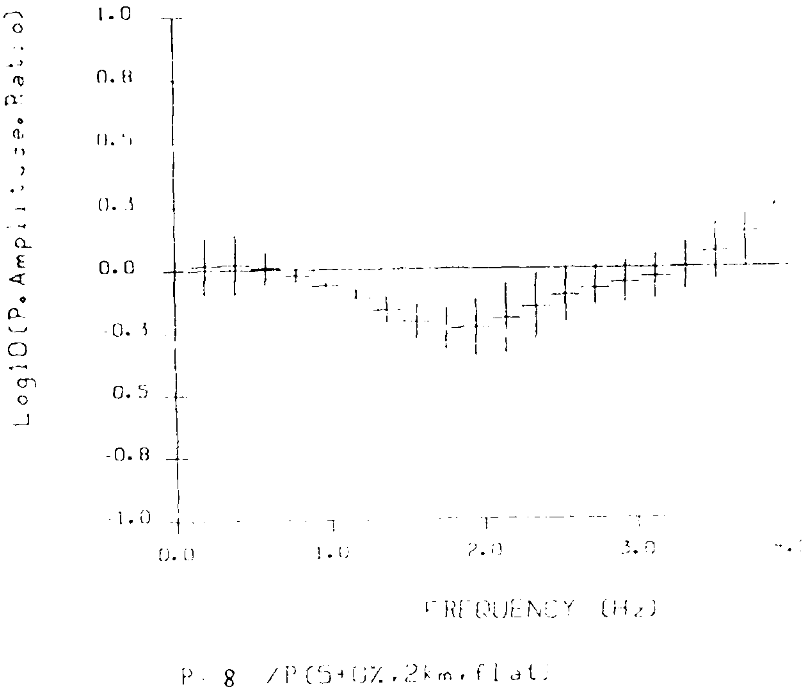


P(' 7)/P(5+0%,2km,flat)



7

Fig. 31


1.0
0.8
0.3
0.0
-0.3
-0.8
-1.0
0.0
1.0
2.0
3.0
FREQUENCY (Hz)
Log10(P.Amplitude.Ratio)
P-8 /P(S+0%,2km,flat)

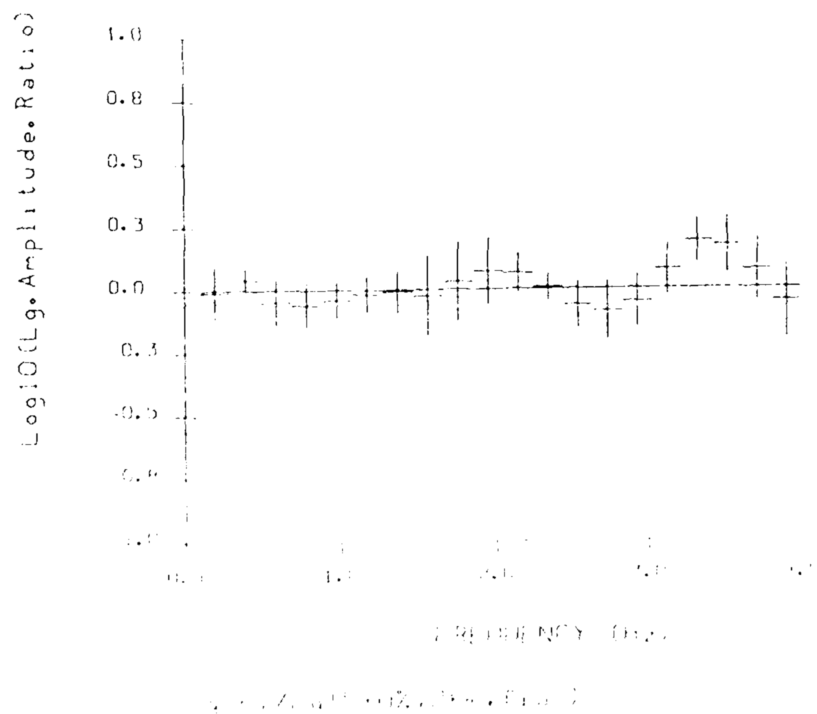
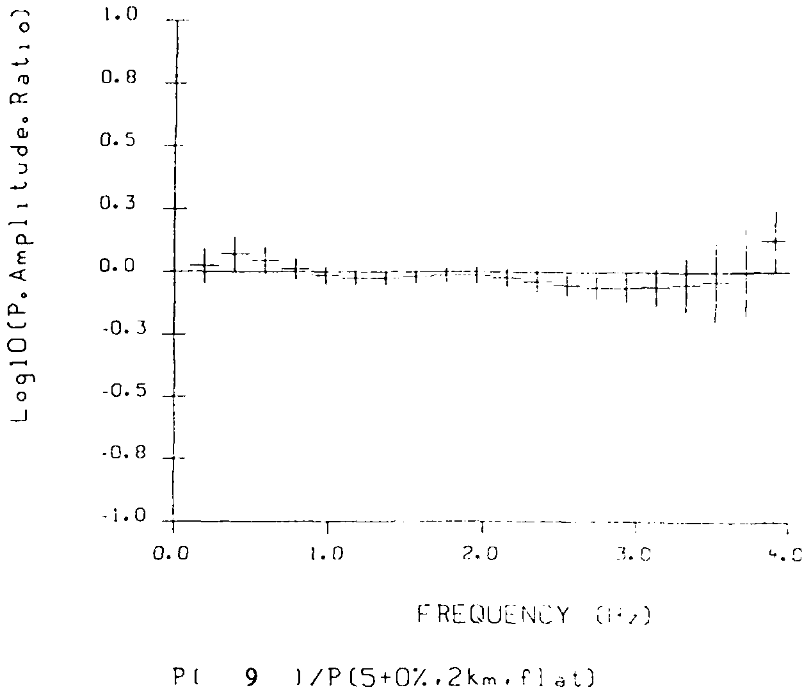

1.0
0.8
0.5
0.3
0.0
Log10(Lg.Amplitude.Ratio)

Fig. 32


Log10(P. Amplitude. Ratio)
1.0
0.8
0.5
0.3
0.0
-0.3
-0.5
-0.8
-1.0
0.0
1.0
2.0
3.0
FREQUENCY
P(9)/P(5+0%,2km,flat)

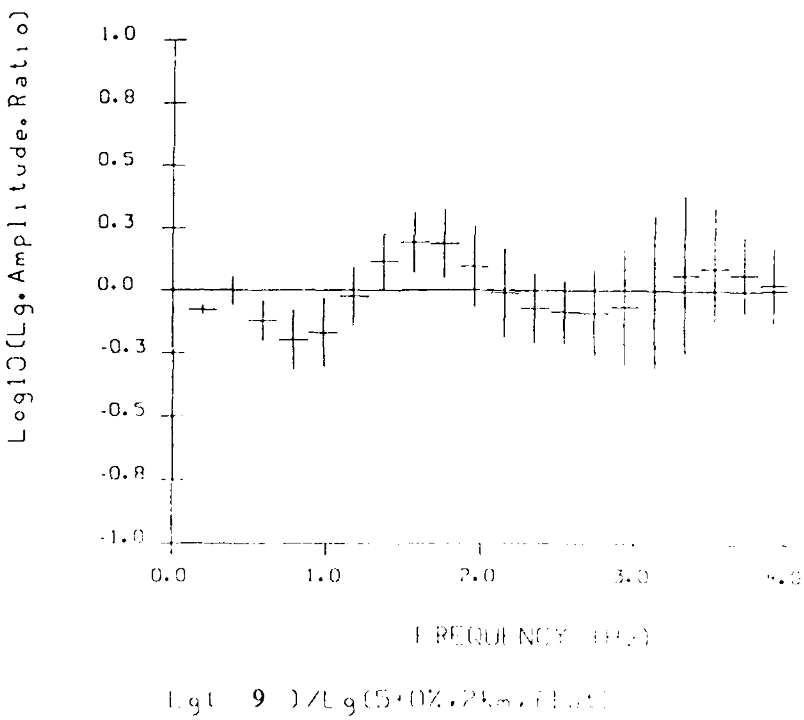
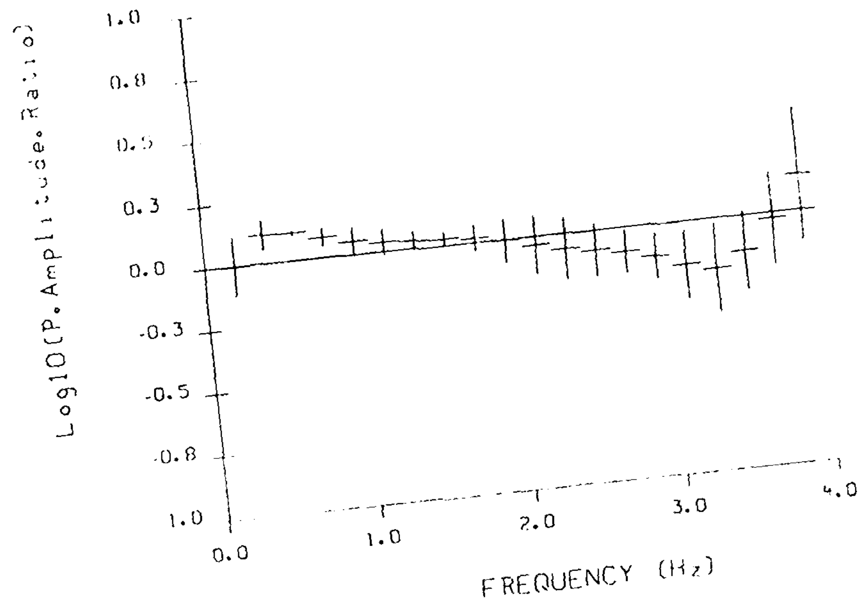
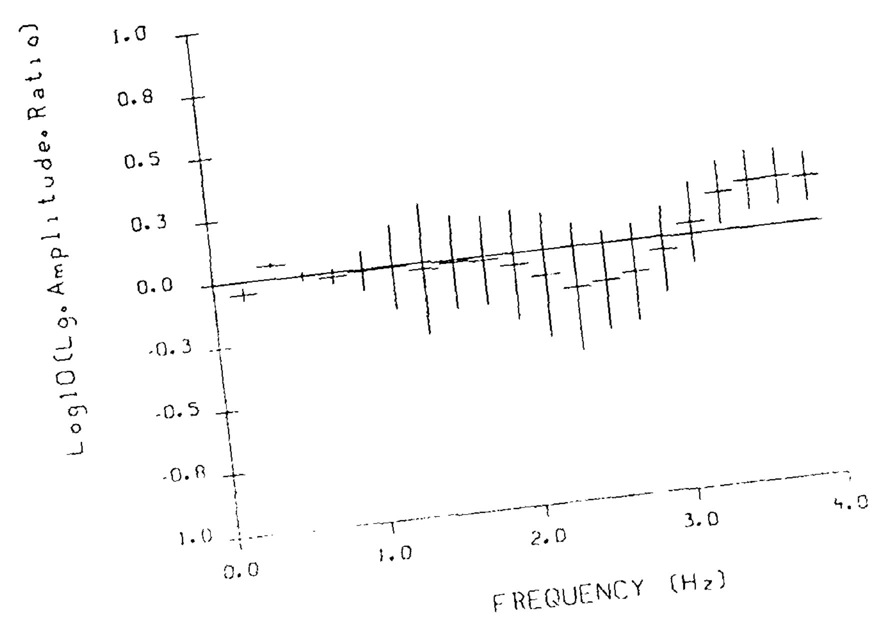

Log10(Lg. Amplitude. Ratio)
1.0
0.8
0.5
0.3
0.0
-0.3
-0.5
-1.0
0.0
1.0

Fig. 33

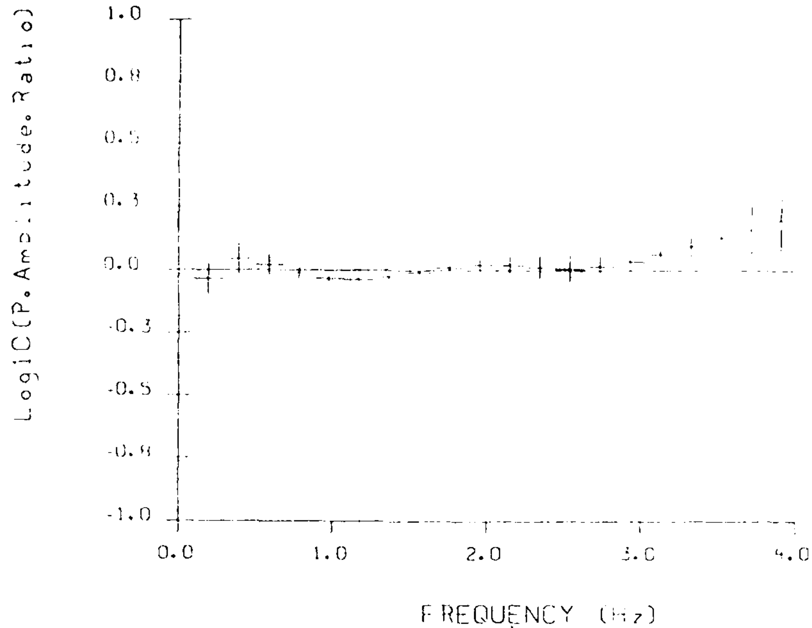


P 10 /P(5+0%.2km.flat)

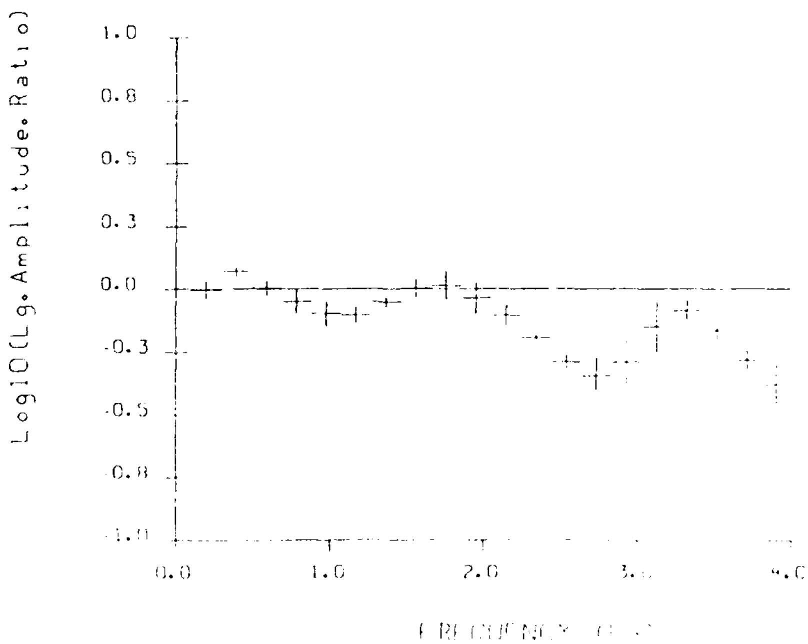


Lg 10/Lg(5+0%,2km,flat)

Fig. 34

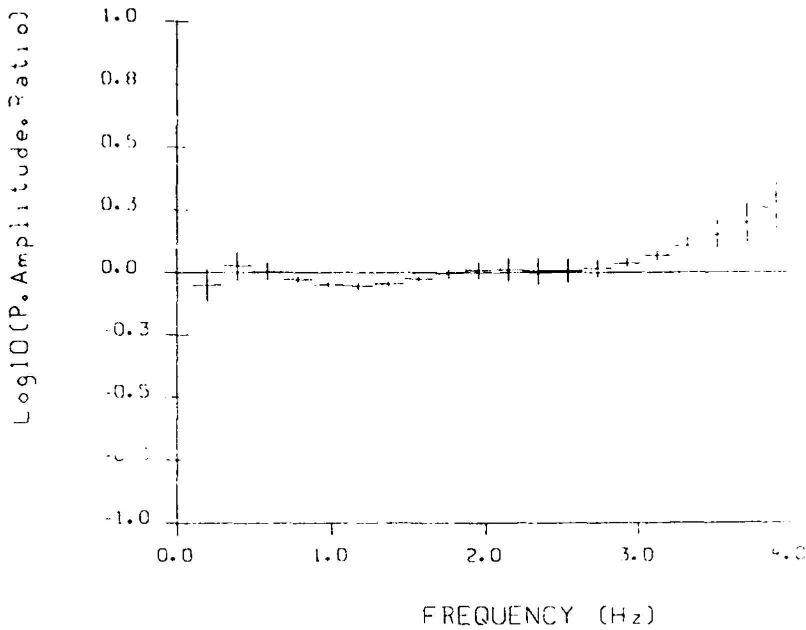


P(11)/P(5+0%,2km,flat)

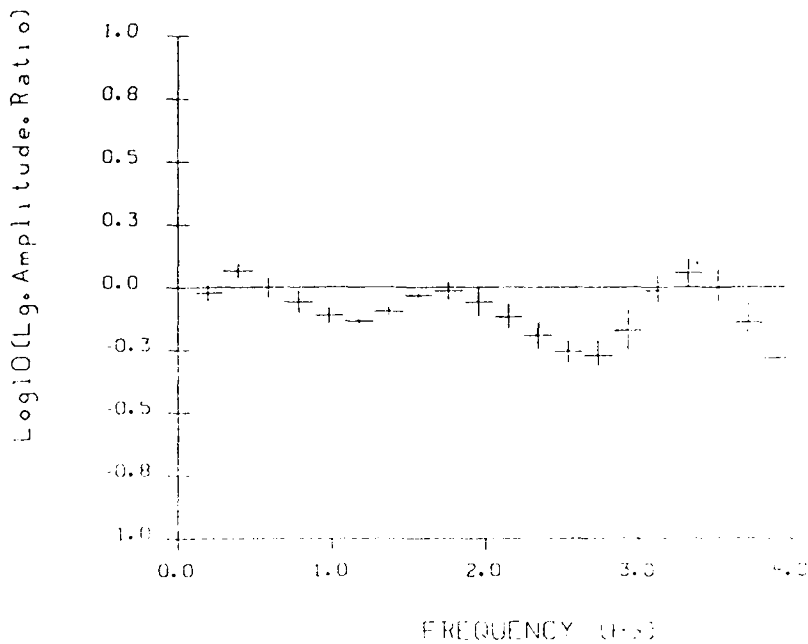


Lg(11)/Lg(5+0%,2km,flat)

Fig. 35

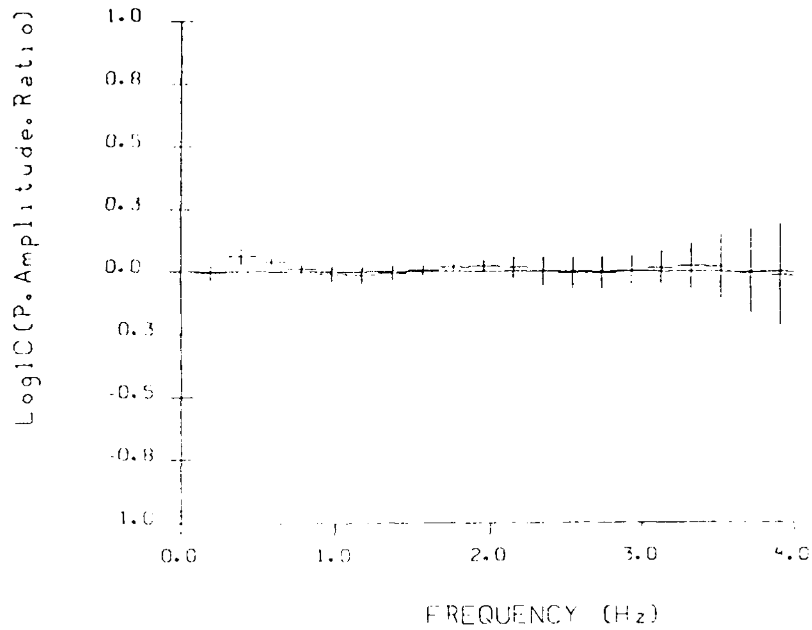


P(12)/P(5+0%,2km,flat)



Lg(12)/Lg(5+0%,2km,flat)

Fig. 36



P(13)/P(5+0%,2km,flat)

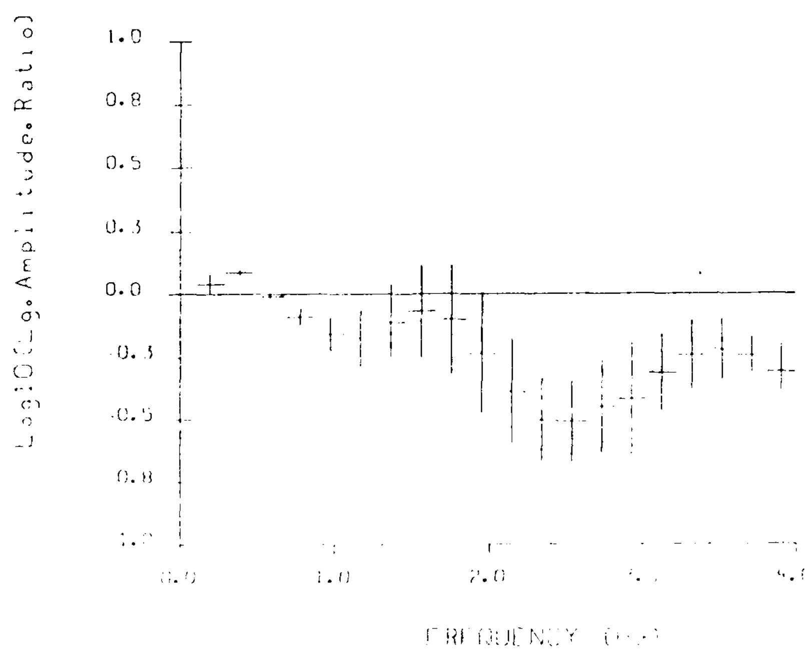


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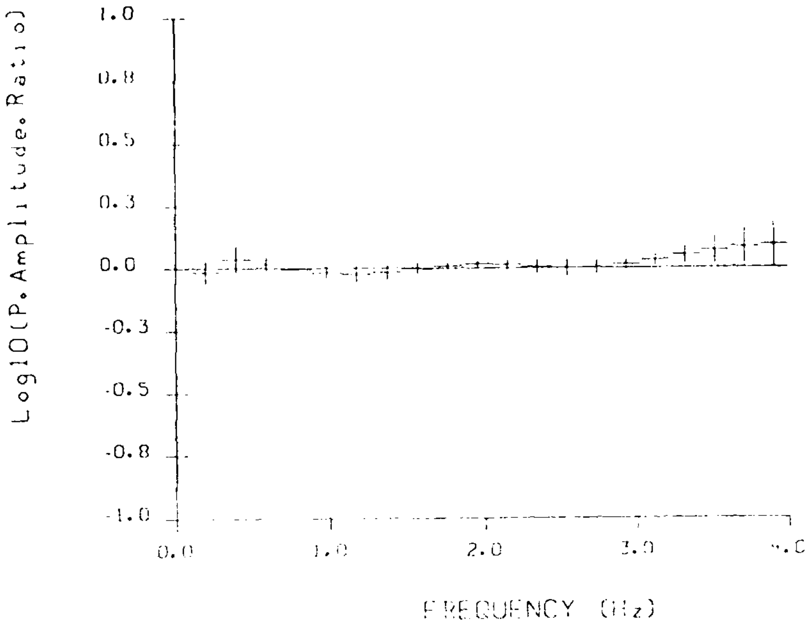
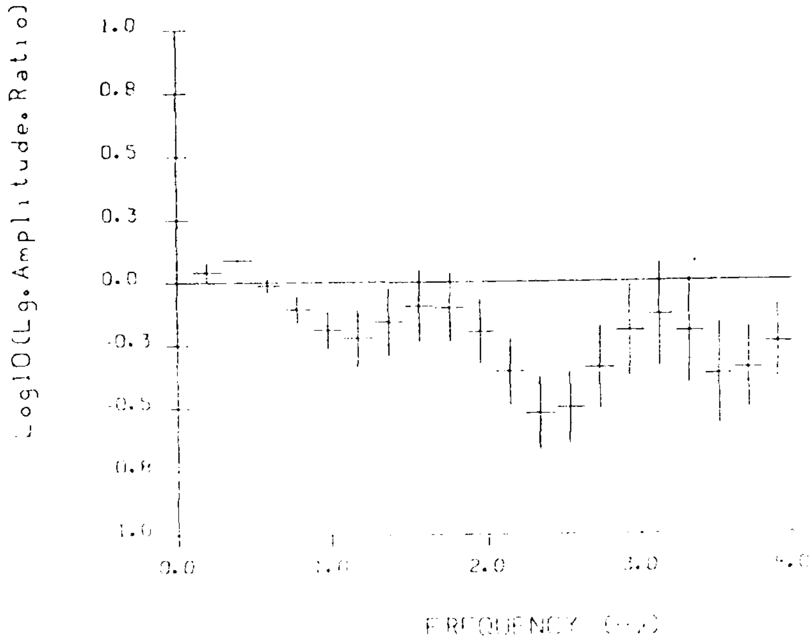
Fig. 37



P(14)/P(5+0%,2km,flat)



Lg 14)/Lg(5+0%,2km,flat)

Fig. 38

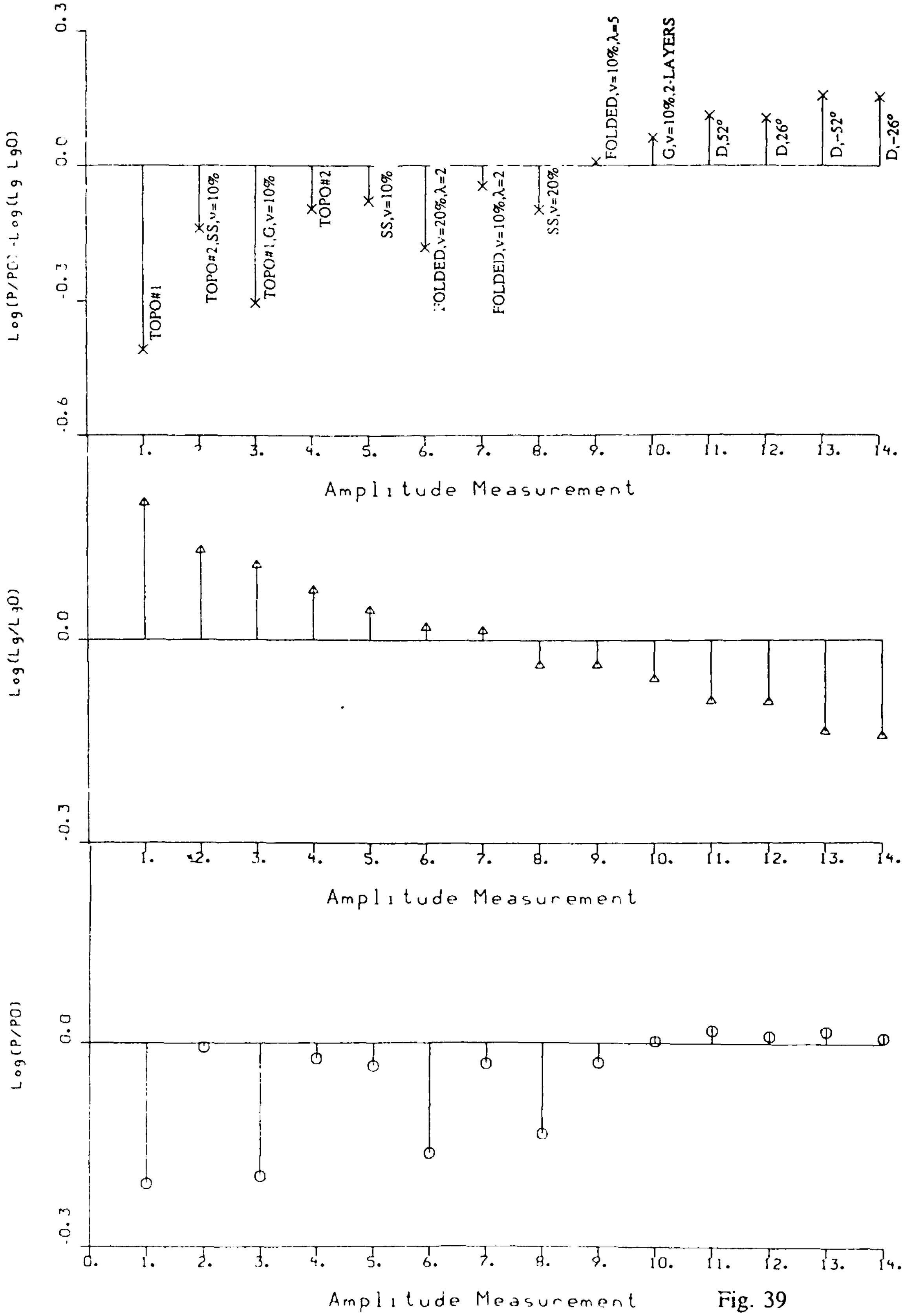

TOPO#1
TOPO#2,SS,v=10%
TOPO#1,G,v=10%
TOPO#2
SS,v=10%
FOLDED,v=20%,λ=2
FOLDED,v=10%,λ=2
SS,v=20%
FOLDED,v=10%,λ=5
G,v=10%,2-LAYERS
D,52°
D,26°
D,-52°
D,-26°
Log(P/P0)-Log(Lg Lg0)
Log(Lg/Lg0)
Log(P/P0)
Amplitude Measurement
Amplitude Measurement
Amplitude Measurement

Fig. 39

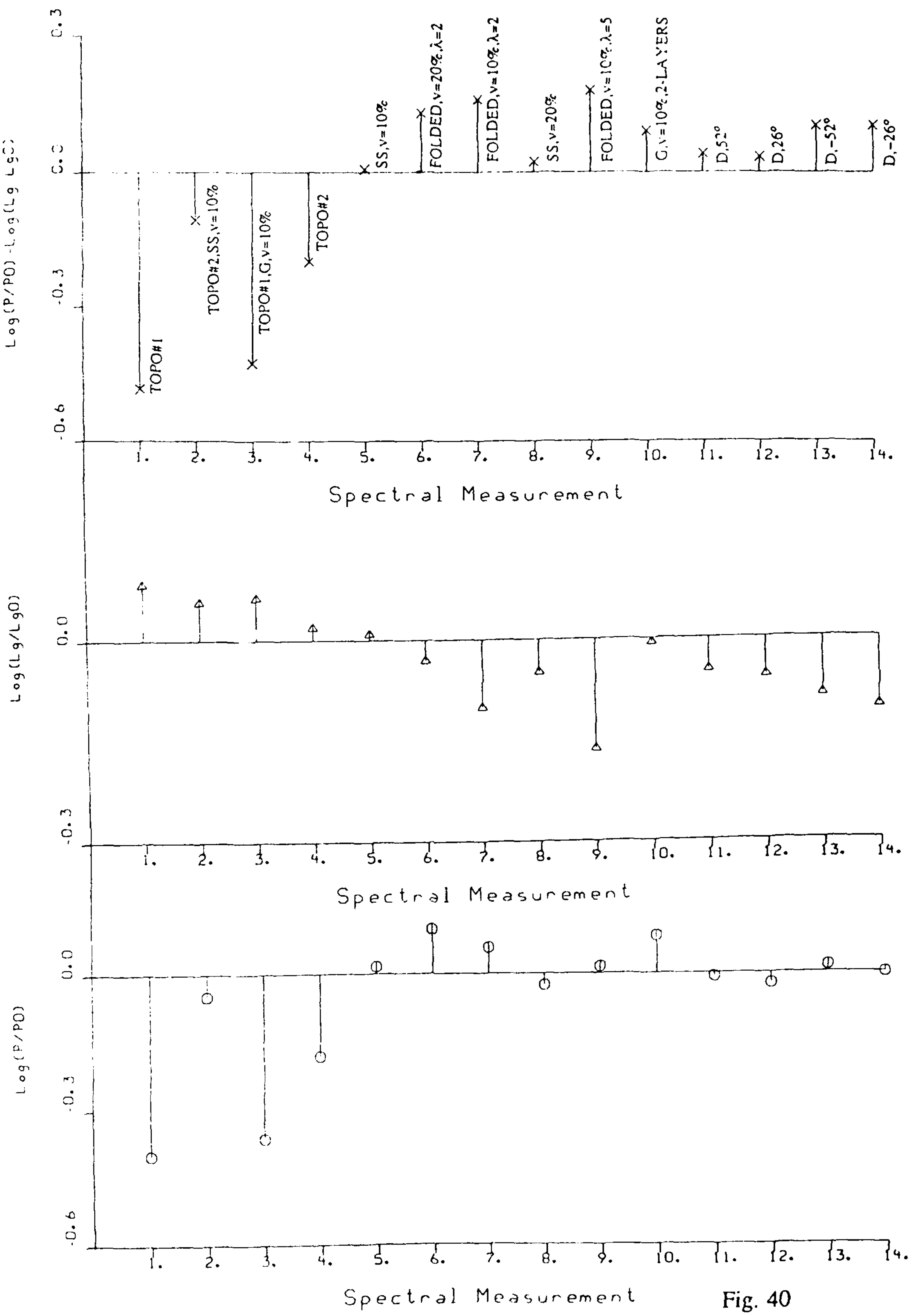
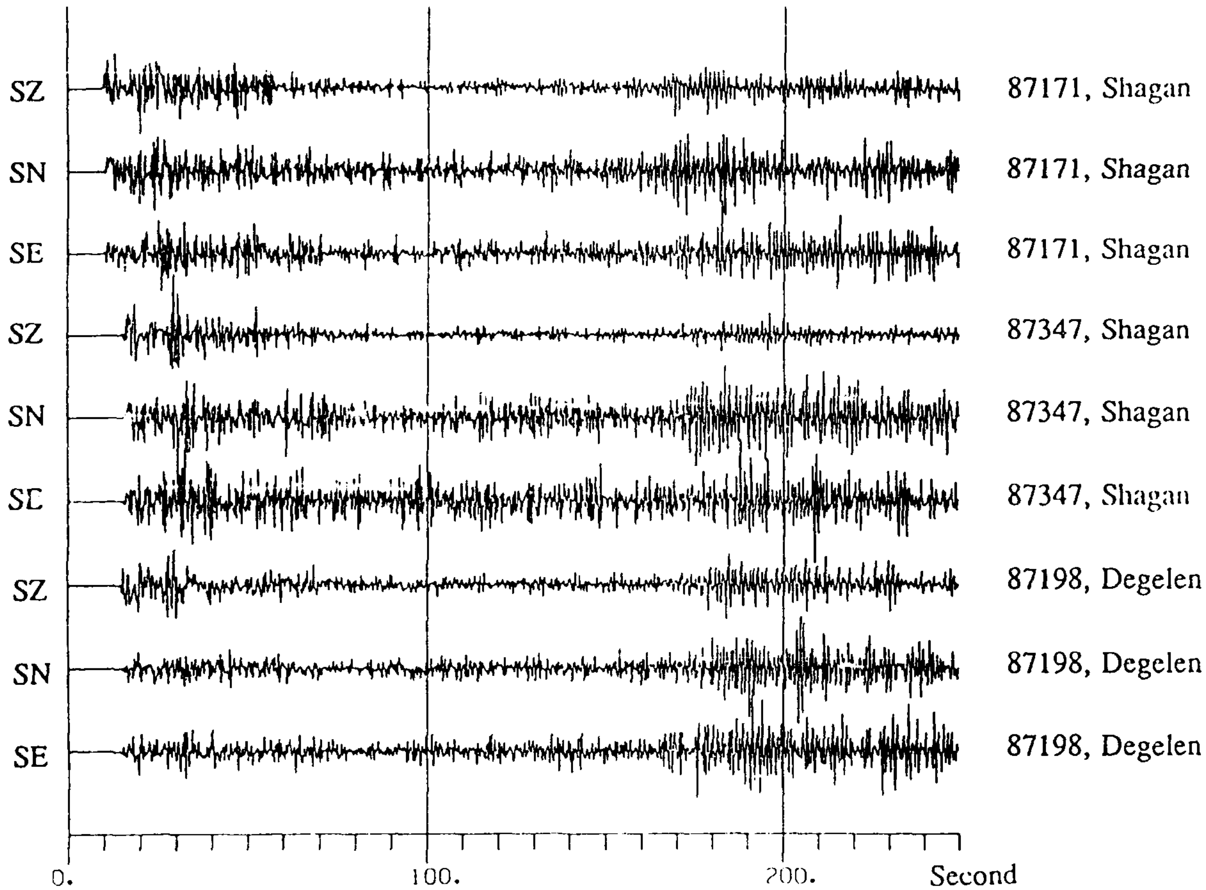

0.3
0.0
-0.3
-0.6
Log(P/PO)-Log(Lg LgO)
TOPO#1
TOPO#2,SS,v=10%
TOPO#1,G,v=10%
TOPO#2
SS,v=10%
FOLDED,v=20%,λ=2
FOLDED,v=10%,λ=2
SS,v=20%
FOLDED,v=10%,λ=5
G,v=10%,2-LAYERS
D,52°
D,26°
D,-52°
D,-26°
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14.
Spectral Measurement
0.0
-0.3
Log(Lg/LgO)
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14.
Spectral Measurement
0.0
-0.3
-0.6
Log(P/PO)
1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14.
Spectral Measurement

Fig. 40



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